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THE PRESSURE DUE TO RADIATION.[1]

By E. F. NICHOLS and G. F. HULL.

As early as 1619 Kepler[2] announced his belief that the solar repulsion of the finely divided matter of comets' tails was due to the outward pressure of light. On the corpuscular theory of light Newton[3] considered Kepler's idea as plausible enough, but he was of the opinion that the phenomenon was analogous to the rising of smoke in our own atmosphere. In the first half of the eighteenth century DeMairan and DuFay[4] contrived elaborate experiments to test this pressure of light theory in the laboratory, but, because of the disturbing action of the gases surrounding the illuminated bodies employed in the measurements, they obtained wholly confusing and contradictory results. Later in the same century Rev. A. Bennet[5] performed further

[1] Presented to *the American Academy of Arts and Sciences*, April, 1903.

[2] DEMAIRAN, *Traité physique et historique de l'Aurore boréale* (2d ed.), pp. 357, 358. Paris, 1754.

[3] *Isaaci Newtoni Opera quae Existant Omnia.* Samuel Horsley, LL.D., R.S.S., Tom. III, pag. 156. Londinium, 1782.

[4] DEMAIRAN, *loc. cit.*, p. 371. This treatise contains also the accounts of still earlier experiments by Hartsoeker, p. 368, and Homberg, p. 369. The later experiments are of more historic than intrinsic interest.

[5] A. BENNET, *Phil. Trans.*, p. 81, 1792.

experiments, but could find no repulsive force not traceable to convection currents in the gas surrounding the body upon which the light was projected, due in his opinion to the heating effect of the rays. Finding no pressure due to radiation, he made the following unique suggestion in support of the wave theory of light:

> Perhaps sensible heat and light may not be caused by the influx or rectilinear projection of fine particles, but by the vibrations made in the universally diffused caloric or matter of heat or fluid of light. I think modern discoveries, especially those of electricity, favor the latter hypothesis.

In the meantime Euler,[1] accepting Kepler's theory attributing the phenomenon of comets' tails to light pressure, had hastened to the support of the wave theory by showing theoretically that a longitudinal wave motion might produce a pressure in the direction of its propagation upon a body which checked its progress. In 1825 Fresnel[2] made a series of experiments, but arrived at no more definite conclusion than that the repulsive and attractive forces observed were not of magnetic nor electric origin.

Crookes[3] believed in 1873 that he had found the true radiation pressure in his newly invented radiometer, and cautiously suggested that his experiments might have some bearing on the prevailing theory of the nature of light. Crookes's later experiments and Zöllner's[4] measurements of radiometric repulsions showed that the radiometric forces were in some cases 100,000 times greater than the light pressure forces with which they had been temporarily confused. Zöllner's experiments are among the most ingenious ever tried in this field of work, and he missed the discovery of the true radiation pressure by only the narrowest margin. An excellent bibliography of the whole radiometric literature is given by Graetz,[5] and an account of some of the older experiments not mentioned above is given by Crookes.[6]

[1] L. EULER, *Histoire de l'Académie royale de Berlin* (2), p. 121, 1746.

[2] A. FRESNEL, *Ann. Chem. et Phys.*, **29**, 57, 107, 1825.

[3] W. CROOKES, *Phil. Trans.*, p. 501, 1873.

[4] F. ZÖLLNER, *Pogg. Ann.*, **160**, 156, 296, 459, 1877.

[5] L. GRAETZ, *Winkelmann's Handbuch der Physik*, 2*b*, p. 262. Breslau, 1896.

[6] W. CROOKES, *loc. cit.*, p. 501.

In 1873 Maxwell,[1] on the basis of the electromagnetic theory, showed that if light were an electromagnetic phenomenon, pressure should result from the absorption or reflection of a beam of light. After a discussion of the equations involved, he says: "Hence in a medium in which waves are propagated there is a pressure in the direction normal to the waves and numerically equal to the energy in unit volume." Maxwell computed the pressure exerted by the Sun on the illuminated surface of the Earth, and added:

> It is probable that a much greater energy of radiation might be obtained by means of the concentrated rays from an electric lamp. Such rays falling on a thin metallic disk, delicately suspended in a vacuum, might perhaps produce an observable mechanical effect.

Apparently independent of Maxwell, Bartoli[2] announced in 1876 that the Second Law of Thermodynamics required the existence of a pressure due to radiation numerically equal in amount to that derived by Maxwell. Bartoli's reasoning holds for all forms of energy streams in space, and is of more general application than Maxwell's equations. Bartoli contrived elaborate experiments to verify this theory, but was balked in the search, as all before him had been, by the complicated character of the gas action, which he found no way of eliminating from his experiments.

After Bartoli's work, the subject was dealt with theoretically by Boltzmann,[3] Galitzine,[4] Guillaume,[5] Heaviside,[6] and more recently by Goldhammer.[7] Fitzgerald,[8] Lebedew,[9] and Hull[10]

[1] J. C. MAXWELL, *A Treatise on Electricity and Magnetism* (1st ed.), **2**, 391. Oxford, 1873.

[2] A. BARTOLI, *Sopra i movementi prodotti della luce et dal calorie*, Florence, Le Monnier, 1876; also *Nuovo Cimento*, **15**, 193, 1884.

[3] L. BOLTZMANN, *Wied. Ann.* **22**, 31, 291, 1884.

[4] B. GALITZINE, *Wied. Ann.*, **47**, 479, 1892.

[5] CH. ED. GUILLAUME, *Arch. de Gen.* (3), **31**, 121, 1894.

[6] O. HEAVISIDE, *Electromagnetic Theory*, **1**, 334. London, 1893.

[7] D. A. GOLDHAMMER, *Ann. der Phys.*, **4**, 834, 1901.

[8] G. F. FITZGERALD, *Proc. Roy. Soc. Dub.*, 1884.

[9] P. LEBEDEW, *Wied. Ann.*, **45**, 292, 1892; ASTROPHYSICAL JOURNAL, **14**, 155, 1902.

[10] G. F. HULL, *Trans. Astron. Soc. Toronto*, p. 123, 1901.

have discussed the bearing of radiation pressure upon the Newtonian law of gravitation, with special reference to the repulsion of comets' tails by the Sun. The theory of radiation pressure, combined with the known properties in negative electrons, has recently been more or less speculatively applied by Arrhenius[1] to the explanation of many cosmical and terrestrial phenomena, among which the following may be mentioned: the solar corona, zodiacal light, gegenschein, comets, origin of cometary and meteoric material in space, the emission of gaseous nebulæ, the peculiar changes observed in the nebula surrounding *Nova Persei*, the northern lights, the variations in atmospheric electricity and terrestrial magnetism and in the barometric pressure. Schwarzschild[2] computed from radiation pressure on small spherical conductors the size of bodies of unit density for which the ratio of radiation pressure to gravitational attraction would be a maximum.

Before the Congrès international de Physique in 1900, Professor Lebedew,[3] of the University of Moscow, described an arrangement of apparatus which he was using at that time for the measurement of light pressure. He summarizes the results already obtained as follows:

> Les résultats des mesures que j'ai faites jusqu'ici peuvent se résumer ainsi: L'expérience montre qu'un faisceau lumineux incident exerce sur les surfaces planes absorbantes et réfléchissantes des pressions qui, aux erreurs près d'observation, sont égales aux valeurs calculées par Maxwell et Bartoli.

No estimate of the "errors of observation" was given in the paper, nor other numerical data. Unfortunately the proceedings of the Paris Congress did not reach the writers, nor any intimation of the methods or results of Professor Lebedew's work, until after the publication of their own preliminary experiments.

The writers[4] presented the results they had obtained by

[1] S. A. ARRHENIUS, *Lehrbuch der kosmischen Physik*, Leipzig, 1903, pp. 149–58, 200–208, 226, 920–5.

[2] K. SCHWARZSCHILD, *Kgl. bayer. Akademie d. Wissenschaften*, **31**, 293, 1901.

[3] P. LEBEDEW, *Rapports présentés au Congrès international de Physique* (2), p. 133. Paris, 1900.

[4] E. F. NICHOLS and G. F. HULL, *Science*, **14**, 588 (October 18, 1901); *Phys. Rev.*, **13**, 293 (November, 1901); ASTROPHYSICAL JOURNAL, **15**, p. 62 (January, 1902).

measurements of radiation pressure at eight different gas pressures, in a preliminary communication to the American Physical Society, meeting with Section B of the American Association at Denver, August 29, 1901. The main arguments underlying the method of measurement of the radiation pressure may here be given.

In the experiments of earlier investigators every approach to the experimental solution of the problem of radiation pressure had been balked by the disturbing action of the gases which it is impossible to remove entirely from the space surrounding the body upon which the radiation falls. The forces of attraction or repulsion, due to the action of gas molecules, are functions, first, of the temperature difference between the body and its surroundings, caused by the absorption by the body of a portion of the rays which fall upon it; and, second, of the pressure of the gas surrounding the illuminated body. In the particular form of apparatus used in the present study, the latter function appears very complicated, and certain peculiarities of the gas action remain inexplicable upon the basis of any simple group of assumptions which the writers have so far been able to make.

Since we can neither do away entirely with the gas nor calculate its effect under varying conditions, the only hopeful approach which remains is to devise apparatus and methods of observation which will reduce the errors due to gas action to a minimum. The following considerations led to a method by which the elimination of the gas action was practically accomplished in the present experiments:

1. The surfaces which receive the radiation, the pressure of which is to be measured, should be as perfect reflectors as possible. This will reduce the gas action by making the rise of temperature due to absorption small, while the radiation pressure will be increased; the theory requiring that a beam, totally reflected, shall exert twice the pressure of an equal beam, completely absorbed.

2. By studying the action of a beam of constant intensity upon the same surface surrounded by air at different pressures,

certain pressures may be found where the gas action is less than at others.

3. The apparatus—some sort of torsion balance—should carry two surfaces symmetrically placed with reference to the rotation axis, and the surfaces of the two arms should be as nearly equal as possible in every respect. The surfaces or vanes should be so constructed that if the forces due to gas action (whether suction or pressure on the warmer surface) and radiation pressure have the same sign in one case, a reversal of the suspension should reverse the gas action and bring the two forces into opposition. In this way a mean of the forces on the two faces of the suspension should be, in part at least, free from gas action.

4. Radiation pressure, from its nature, must reach its maximum value instantly, while observation has shown that gas action begins at zero and increases with length of exposure, rising rapidly at first, then more slowly to its maximum effect, which, in many of the cases observed, was not reached until the exposure had lasted from two and a half to three minutes. For large gas pressures an even longer exposure was necessary to reach stationary conditions. The gas action may be thus still further reduced by a ballistic or semi-ballistic method of measurement.

Ballistic observations of radiation pressure were made at air pressures ranging from 96.3 mm to 0.06 mm of mercury. The average radiation pressure of the standard beam was found to be 1.05×10^{-4} dyne, with a probable error of 6 per cent. To compare this value of the pressure with the theoretical value as given by the Maxwell-Bartoli formula, $p = \frac{E(1+\rho)}{V}$, it was necessary to measure E, the energy of the beam. This was done by a bolometric method in which the measurement of the energy was made to depend upon the resistance of the bolometer strip. Using the value of the energy thus obtained and 0.92[1] as the reflection coefficient of the silver surfaces, it was found that the

[1] This value was obtained from the measurements of Langley, Rubens, Nichols, and Paschen for the assumed mean wave-length of the beam.

pressure directly observed was about 20 per cent. lower than that computed from the Maxwell-Bartoli formula. After the publication of the paper it was found that an error had been made in the measurement of the resistance of the bolometer strip, owing to a fault in its construction. A new estimation of the resistance gave an energy value which brought the theoretical value of the pressure very close to that found by direct measurement. But another method of measuring the energy was adopted in the later experiments described in this paper.

In the number of the *Annalen der Physik* for November, 1901, Professor Lebedew[1] published the results of a more varied series of measurements of radiation pressure than the early measurements of the present writers. The principal difference between the methods employed by him and by the writers for determining the pressure was that he used very thin metallic vanes surrounded by gas at extremely low pressures, thus following Maxwell's suggestion literally, while the writers used silvered glass vanes and worked at large gas pressures for which the gas action had been carefully and exhaustively studied and found to be negligibly small for short exposures. From our knowledge of the variation of gas action in different vacua, we feel sure that our method would not have been successful in high vacua because of the relatively large gas action. Professor Lebedew's own results, with blackened vanes of lower heat conductivity, show that his success in eliminating gas disturbance was due to the high heat conductivity of thin vanes rather than to the high vacua employed.

Professor Lebedew's[2] estimate of the accuracy of his work is such as to admit of possible errors of 20 per cent. in his final results. An analysis of Professor Lebedew's paper and comparison with our preliminary experiments seem to show that his accidental errors were larger than ours, but through the undiscovered false resistance in the bolometer our final results were somewhat farther from the theory than his. Either of the above researches would have been sufficient to establish the *existence*

[1] P. LEBEDEW, *Ann. der Phys.*, **6**, 433, 1901.

[2] P. LEBEDEW, *Ann. der Phys.*, **6**, 457, 1901.

of a pressure due to radiation, but neither research offered, in our judgment, a satisfactory *quantitative* confirmation of the Maxwell-Bartoli theory.

LATER PRESSURE MEASUREMENTS.

Description of apparatus: the torsion balance.—The form of suspension of the torsion balance, used to measure radiation pressure in the present study, is seen in Fig. 1. The rotation axis ab was a fine rod of drawn glass. A drawn-glass cross-arm c, bent down at either end into a small hook, was attached to the axis. The surfaces C and D, which received the light beam, were circular microscope cover-glasses, 12.8 mm in diameter and 0.17 mm thick, weighing approximately 51 mg each. To distinguish the two vanes from each other, in case individual differences should appear in the measurements, and also to mark the two faces of each vane for subsequent recognition, a letter C was marked on one, and D on the other, by diamond scratches. Through each glass a hole 0.5 mm or less in diameter was drilled near the edge, by means of which the glasses could be hung on the hooks on the cross-arm c. On opposite sides of the rotation axis at d two other drawn-glass cross-arms were attached. The cover-glasses slipped easily between these, and were thus held securely in one plane. Farther down on ab, a small silvered plane mirror m_1 was made fast at right angles to the plane of C and D. This mirror was polished bright on the silver side, so that the scale at S_5 (Fig. 2) could be read in either face. A small brass weight m_3 (Fig. 1), of 452 mg mass and of known dimensions, was attached at the lower end of ab. The cover-glasses which served as vanes were silvered and brilliantly polished on the silvered sides, and so hung on the small hooks that both silver faces or both glass faces were presented to the light. A quartz fiber f_2, 3 cm long, was made fast to the upper end of ab, and to the lower end of a fine glass rod d_1 which carried a horizontal magnet m_2. The rod d_1 was in turn suspended by a short fiber to a steel pin e, which could be raised or lowered in the bearing h. The whole was carried by a bent glass tube t, firmly fastened to a solid brass foot F, resting on a plane

ground-glass plate *P*, cemented to a brass platform mounted on three leveling screws not shown. A bell-jar *B*, 25 cm high and 11 cm in diameter, covered the balance. The flange of the bell-jar was ground to fit the plate *P*. A ground-in hollow glass stopper fitted the neck of the bell-jar, which could thus be put in

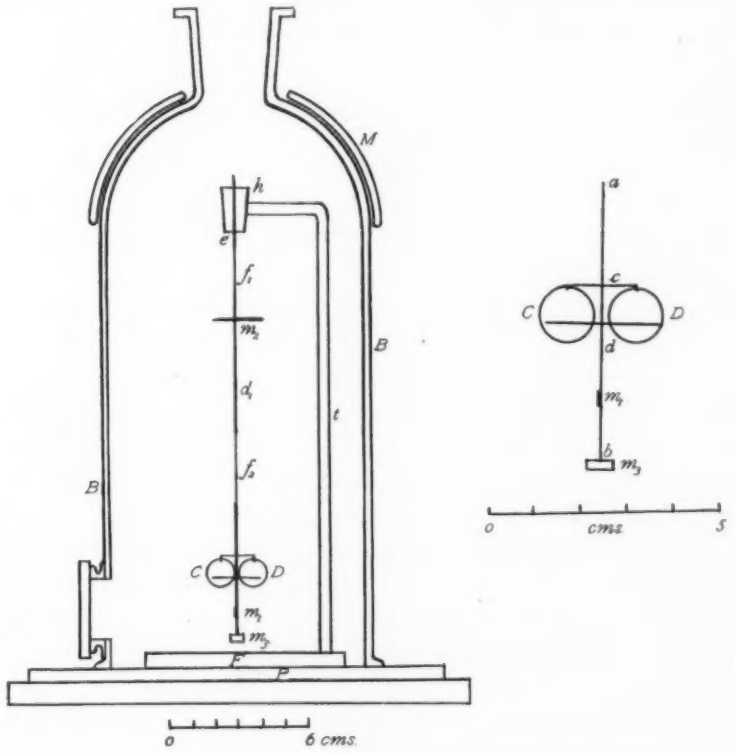


FIG. 1.

connection with a system of glass tubes leading to a Geissler mercury pump, a MacLeod pressure gauge, and a vertical glass tube dipping into a mercury cup and serving as a rough manometer for measuring the larger gas pressures employed during the observations. The low pressures were measured on the MacLeod gauge in the usual way. A semicircular magnet *M*, fitted to the vertical curvature of the bell-jar, was used to direct the suspended magnet m_2 and thus to control the zero

position of the torsion balance. By turning M through 180°, the opposite faces of the vanes C and D could be presented to the light.

THE ARRANGEMENT OF APPARATUS.

A horizontal section of the apparatus through the axis of the light beam is shown in Fig. 2. The white-hot end of the horizontal carbon S_1, of an A. T. Thompson 90° arc-lamp, fed by alternating current, served as a source. The arc played against the end of the horizontal carbon from the vertical carbon which was screened from the lenses L_1 and L_2 by an asbestos diaphragm d_2. A lens, not shown, projected an enlarged image of the arc and carbons on an adjacent wall, so that the position of the carbons and the condition of the arc could be seen at all times by both observers.

The cone of rays passing through the small diaphragm d_2 fell upon the glass condensing lenses L_3, L_4. At d_3 a diaphragm, 11.25 mm in diameter, was interposed, which permitted only the central portion of the cone of rays to pass. Just beyond d_3, the beam passed to a shutter at S_2. This shutter was worked by a magnetic escapement, operated by the seconds contact of a standard clock. The observer at T_1 might choose the second for opening or closing the shutter, but the shutter's motion always took place at the time of the second's contact in the clock. Any exposure was thus of some whole number of seconds' duration. The opening in the shutter was such as to let through, at the time of exposure, all of the direct beam which passed through d_3, but to shut out stray light. Just beyond the shutter and attached to the diaphragm d_5 was a 45° glass plate which reflected a part of the beam to the lens L_5, by means of which an image of d_3 was projected upon one arm of a bolometer at R. The glass lens L_3 focused a sharp image of the aperture d_3 in the plane of the vanes of the torsion balance B_1, under the bell-jar. The bell-jar was provided with three plate-glass windows W_1, W_2, W_3. The first two gave a circular opening 42 mm in diameter, and through the third, deflections of the balance were read by a telescope and scale. The lens L_3 was arranged to move horizontally between the stops S_3 and S_4. These were

so adjusted that when the lens was against S_3 the sharp image of the aperture d_3 fell centrally upon one vane; and when against S_4 the image fell centrally upon the other. This adjustment, which was a very important one, was made by the aid of a telescope T_2, mounted on the carriage of a dividing engine. This was used to observe and measure the position of the rotation axis, as well as the positions of the images of d_3, when the lens L_3 was against the stops. For the latter measurements the vanes could be moved out of the way by turning the suspension through 90° by the control magnet M (Fig. 1).

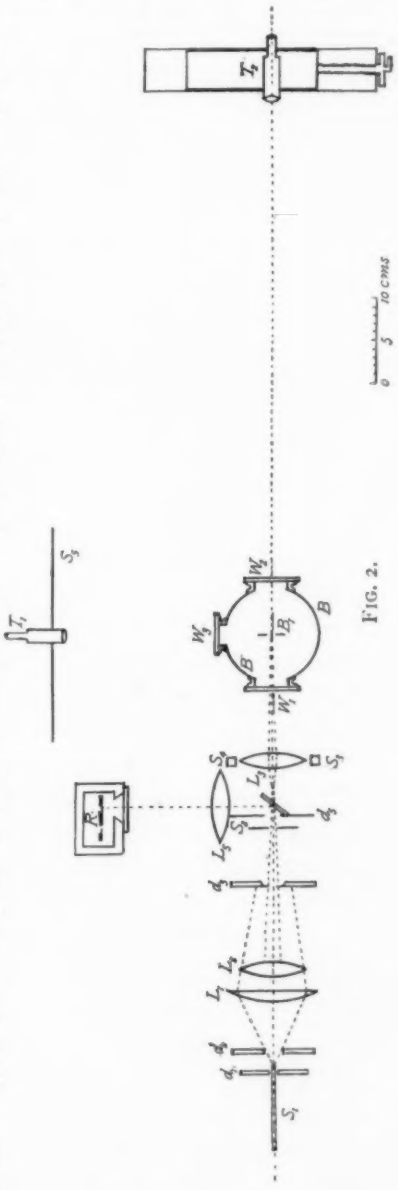


FIG. 2.

To make sure that the balance as used was entirely free from any magnetic moment or disturbance, the small magnet m_2 was clamped in one position to maintain a constant zero, and the period of the balance was accurately measured with the axis of the large magnet M in the vertical plane of the vanes and again when the axis was at right angles to the plane of the vanes. Several series of this sort failed to show a difference of 0.1 second in the period of the balance for the two positions of the magnet.

The bolometer at R (Fig. 2) was of sheet platinum 0.001 mm thick, rolled in silver. The strip was cut out in the form shown

in Fig. 3, and mounted on a thin sheet of slate *S*. Two windows had been cut in the slate behind the strips at *ABCD* where the silver had been removed leaving the thin platinum. The platinum surfaces were blackened by Kurlbaum's process. The image from L_5 (Fig. 2), fell at *D*. The silver ends between *A*

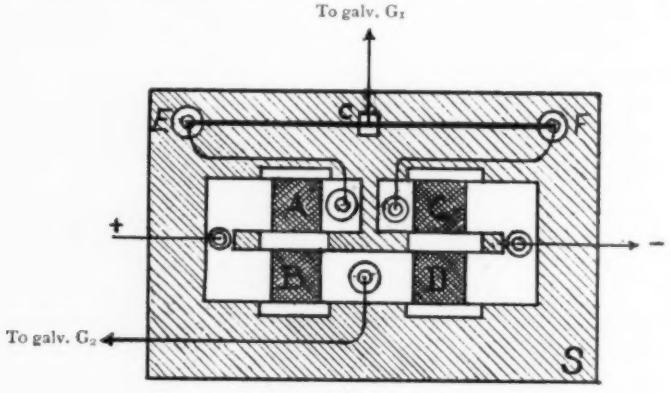


FIG. 3.

and *C* were connected with *E* and *F* respectively. On the heavy wire *EF* a sliding contact *c* served to balance the bridge, all four arms of which are shown in the figure.

METHODS OF OBSERVATION.

The observations leading to the results given later were of three different kinds: (1) the calibration of the torsion balance; (2) the measurement of the pressure of radiation in terms of the constant of the balance; and (3) the measurement of the energy of the same beam in erg-seconds by the rate of temperature rise of a blackened silver disk, of known mass and specific heat.

1. The determination of the constant of the torsion balance was made by removing the vanes *C* and *D* and accurately measuring the period of vibration. Its moment of inertia was easily computed from the masses and distribution of the various parts about the axis of rotation. The moment of torsion for 1 mm deflection on a scale 105 cm distant was 0.363×10^{-5} dyne$\times$cm. This value divided by one-half the distance between the centers

of the light spots on the two vanes gave the force in dynes per scale division deflection. As the light spots were circles 11.25 mm in diameter the area of the image was very nearly 1 sq. cm, hence the above procedure gave roughly the pressure in dynes per square centimeter.

2. In the measurements of radiation pressure, it was easier to refer the intensity of the beam at each exposure to some arbitrary standard which could be kept constant than to try to hold the lamp as steady as would otherwise have been necessary. For this purpose, the bolometer at R (Fig. 2) was introduced, and simultaneous observations were made of the relative intensity of the reflected beam by the deflection of the galvanometer G_2, and the pressure due to the transmitted beam by the deflection of the torsion balance. The actual deflection of the balance was then reduced to a deflection corresponding to a galvanometer deflection of 100 scale divisions. The galvanometer sensitiveness was carefully tested at the beginning and end of each evening's work. All observations of pressure were thus reduced to the pressure due to a beam of fixed intensity.

At each series of radiation pressure measurements, two sets of observations were made. In one of these sets, static conditions were observed, and in the other, the deflections of the balance due to short exposures were measured. In the static observations, each vane of the balance was exposed in turn to the beam from the lamp, the exposures lasting until the turning points of the swings showed that stationary conditions had been reached. The moment of pressure of radiation and gas action combined would thus be equal to the product of the static deflection and the constant of the balance. The torsion system was then turned through 180° by rotating the outside magnet, and similar observations were made on the reverse side of the vanes. All turning-points of the swinging balance in these observations were recorded. From the data thus obtained the resultant of the combined radiation and gas forces could be determined for the time of every turning-point. Every value was divided by the deflection at standard sensitiveness of the galvanometer G_2 read at the same time and was thus reduced to standard lamp.

Results thus obtained, together with the ballistic measurements, showed the direction and extent of the gas action as well as its variation with length of exposure.

The reasons for reversing the suspension follow: The beam from the lamp, before reaching the balance, passed through three thick glass lenses and two glass plates. All wave-lengths destructively absorbed by the glass were thus sifted out of the beam by the time it reached the balance vanes. The silver coatings on the vanes absorbed therefore more than the glass. The radiation pressure was always away from the source, irrespective of the way the vanes were turned, while the gas action would be exerted mainly on the silvered sides of the vanes.

At the close of the pressure and energy measurements, when the reflecting power of the silver faces of the vanes was compared with that of the glass-silver faces, the reflection from the silver faces was found very much higher than that for the glass faces backed by silver. This result was the more surprising because the absorption of the unsilvered vanes was found by measurement to be negligibly small.[1] This unexpected difference in reflecting power of the two faces of the mirrors prevented the elimination of the gas action, by the method described, from being as complete as had been hoped for. But by choosing a gas pressure where the gas action after long exposure is small, the whole gas effect during the time of a ballistic exposure may be so reduced as to be of little consequence in any case.

By exposing each of the vanes in turn and by reversing the suspension and averaging results, nearly all errors due to lack of symmetry in the balance or in the position of the light images with reference to the rotation axis, or errors due to lack of uniformity in the distribution of intensity in different parts of the image, could be eliminated.

The changing character of the gas action, both with time of exposure and gas pressure surrounding the balance vanes, is well illustrated in eight series of static observations in which the

[1] LORD RAYLEIGH records a similar difference between the reflection from air-silver and glass-silver surfaces. *Scientific Papers*, Cambridge, **2**, 538–539, 1900.

glass faces of both vanes were exposed.[1] The results obtained

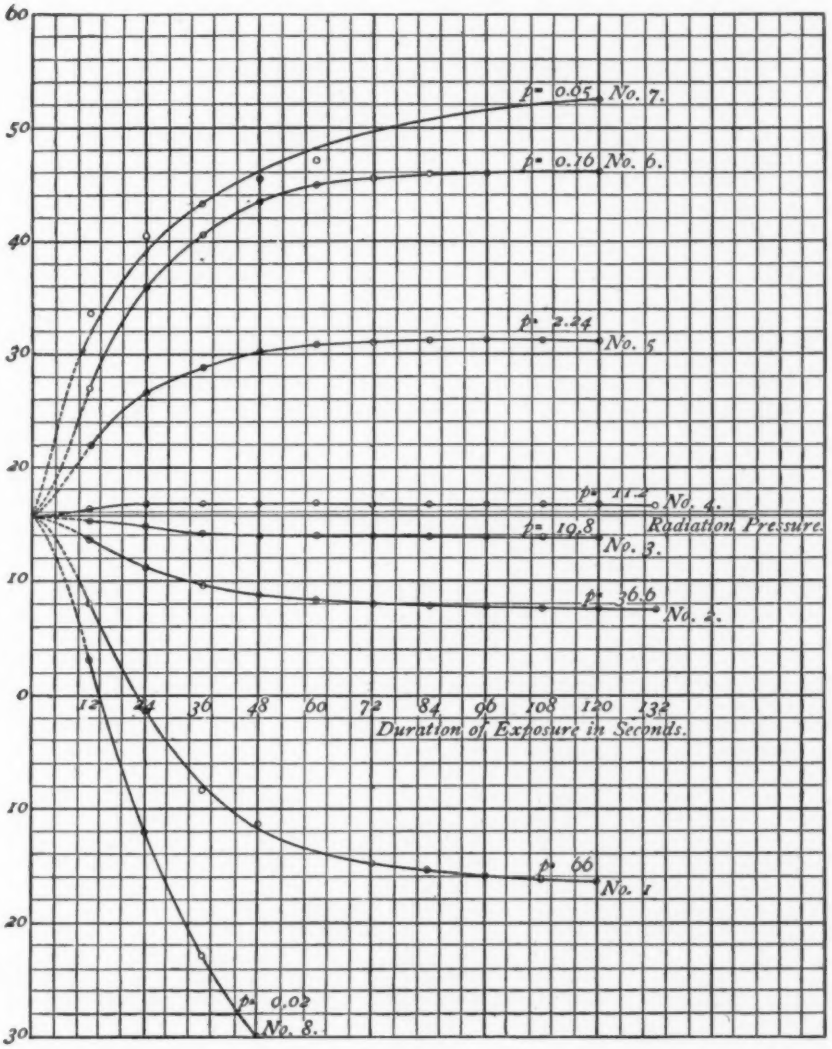


FIG. 4.

on the two vanes were averaged and plotted as curves in Fig. 5,

[1] Observations were also made on the silver faces, but the gas action when the glass faces were exposed was nearly double that for the silver faces, so the least favorable case is shown.

where static deflections due to combined radiation pressure and gas action are shown as ordinates and duration of exposure, in seconds, as abscissæ.[1] A horizontal line through the diagram gives the mean value of the moment of radiation pressure computed from the data in Table I. Decrease of the deflection with time indicates gas repulsion on the warmed silver faces and increase in deflection, gas suction. It will be seen from the curves that beginning at a gas pressure of 66 mm of mercury, the gas action was repulsion changing to suction in passing from 19.8 to 11.2 mm. In the last two cases the total gas action is small. For lower pressures the suction increases to 0.05 mm. At a gas pressure of 0.02 mm the gas action is again a strong repulsion.

The curves indicate the existence of two gas pressures, at which the gas action in our arrangement of apparatus should be zero, one between 19.8 and 11.2 mm and the other between 0.05 and 0.02 mm.[2] The former region was chosen for the ballistic measurements and nearly all of the observations were made at a gas pressure of approximately 16 mm. Even for the two pressures where the decrease in the static deflection was most rapid, *i. e.*, at gas pressures of 66 and 0.02 mm, the first throw was always in the direction of radiation pressure. The gas action is strongly influenced by very slight changes in the inclination of the plane of the vanes to the vertical and also by any object introduced under the bell-jar anywhere near the vanes. For instance, a very considerable effect was observed when a small vessel of phosphoric anhydride was placed under the jar behind the vanes, though the nearest wall of the vessel was separated from the vanes by a distance of at least 3 cm.

During the observations, the polished silver coatings on the vanes deteriorated rapidly; new coatings rarely lasted for more than two evenings' work. As the balance had to be removed

[1] Ordinates of the curves are proportional to moments.

[2] Crookes in his work with the radiometer discovered certain gas pressures for which the combined gas and radiation forces neutralized, but as he did not discriminate between forces due to radiation and gas forces his results were apparently capricious and his reasoning somewhat confused. See *Phil. Trans.*, p. 519, 1875.

and the mirrors taken from the hooks, silvered, polished, and replaced a great number of times during the entire series of measurements, although great care was taken in setting the plane of the vanes vertical, it is not likely that precisely the same conditions for gas action were ever repeated. The principal value of the static results was in indicating favorable gas pressures for work, rather than affording quantitative estimates of the gas action in short exposures. The dotted parts of the curves are not based on results of observation and might perhaps have been omitted without loss.

It was plain, therefore, that further elimination of the gas action must be sought in exposures so short that the gas action would not have time to reach more than a small fraction of its stationary value. This led to the method of ballistic observations.

THE BALLISTIC OBSERVATIONS.

In passing from the static to the ballistic observations it must always be possible to compute the static equivalent of the ballistic swings. Furthermore the exposures should be made as short as possible without reducing the size of the swing below a value which can be accurately measured.

If the exposure lasts for one-half the period of the balance, the deflection, if the gas action be small, and the damping zero, is equal to 2θ where θ is the angle at which the torsion of the fiber will balance the moment produced by the radiation pressure. If the duration of the exposure be one-quarter of the period of the balance, the angle of deflection is $\theta_1/\sqrt{2}$. The deflection is thus reduced by 30 per cent., but the effect of the gas action is reduced in greater proportion. It was decided, therefore, to expose for six seconds, one-quarter of the balance period. Neglecting the gas action, the equation[1] of motion of the balance is given by

$$\kappa\frac{\partial^2\theta}{\partial t^2} + 2\epsilon\frac{\partial\theta}{\partial t} = -G\theta + L\ ,$$

[1] We are justified in using quantitatively this equation, containing a damping term proportional to the velocity, because the amplitudes of the successive swings of the torsion balance, when no energy fell upon the vanes, were found experimentally to follow accurately the exponential law.

where κ = the moment of inertia of the torsion balance,

ϵ = the damping constant,

G = the moment of torsion of the fiber for $\theta = 1$ radian,

and L = the moment of the radiation force.

The solution of this equation is

$$\theta = \frac{L}{G}\left\{1 - e^{-\frac{\epsilon}{\kappa}t}\cos\sqrt{\frac{G}{\kappa} - \frac{\epsilon^2}{\kappa^2}}\,t\right\},$$

$$= \frac{L}{G}\left\{1 - e^{-\frac{\epsilon}{\kappa}t}\cos 2\pi\frac{t}{T}\right\}, \qquad (1)$$

the constants of integration having been determined from the condition that

$$\theta = \frac{\partial\theta}{\partial t} = 0 \text{ when } t = 0 .$$

When

$$t = \frac{T}{4},\ \theta = \frac{L}{G} \text{ and } \frac{\partial\theta}{\partial t} = \frac{L}{G}\left(\frac{\epsilon}{\kappa}e^{-\frac{\epsilon}{\kappa}t}\cos 2\pi\frac{t}{T} + e^{-\frac{\epsilon}{\kappa}t}\frac{2\pi}{T}\sin 2\pi\frac{t}{T}\right). \qquad (2)$$

The light being cut off when $t = \frac{T}{4}$, the equation of motion becomes

$$\kappa\frac{\partial^2\theta}{\partial t^2} + 2\epsilon\frac{\partial\theta}{\partial t} = -G\theta , \qquad (3)$$

the solution of which is $\theta = Ae^{-\frac{\epsilon}{\kappa}t}\cos\left(2\pi\frac{t}{T} + a\right)$, where A and a can be determined by the conditions imposed by equation (2). Neglecting very small quantities, the value of the amplitude A is expressed by the equation

$$A = \frac{L}{G}\left\{1 + r + \frac{2}{\pi}r^{\frac{1}{2}}\log\left(\frac{1}{r}\right)\right\}^{\frac{1}{2}}, \qquad (4)$$

where r is the ratio of successive amplitudes of the damped vibrations. If $r = 1$, that is, if the motion is undamped, $A = \frac{L}{G}\sqrt{2}$. In the partial vacuum used in the experiments (16 mm of mercury, a value chosen from the curves in Fig. 4), r was found to be equal to 0.783; consequently $A = 1.357\,\frac{L}{G}$. (5)

From this it is seen that the total angle of deflection of the torsion balance in the ballistic measurements is equal to 1.357 times the angle at which the moment of the torsion of the fiber balances the moment of the radiation pressure.

The duration of exposure was always six seconds without appreciable error, but the period of the balance on account of slight accidental shifting of small additional masses upon the counterpoise weight m_3 (Fig. 1), differed from twenty-four seconds sometimes by 1 per cent. It is necessary, therefore, to find the error in the deflection due to this variation in the period. This is done by making $t = \frac{T}{4} + \delta$ in equation (2) and in introducing the new conditions in equation (3). But it is simpler and sufficiently accurate to assume the motion as undamped. For this condition the amplitude

$$A = \frac{L}{G}\left\{2 + 2 \sin 2\pi \frac{\delta}{T}\right\}^{\frac{1}{2}} = \sqrt{2}\frac{L}{G}\left(1 + \pi \frac{\delta}{T}\right) \text{ nearly.}$$

For $T = 23.75$ seconds, $\frac{T}{4} = 5.94$ and $\delta = 0.06$. Hence

$$A = \sqrt{2}\frac{L}{G}(1.008).$$

If $\delta = 0$, $A = \sqrt{2}\frac{L}{G}$, consequently an error of 1 per cent. in T causes an error of 0.8 per cent. in A.

To make sure that the observed radiation pressures depended only on the intensity of the beam, and were uninfluenced by the wave-length of the incident energy, the ballistic observations of pressure, the thermal measurements of intensity, and the determination of the reflection coefficients, were carried out for three entirely different wave-groups of the incident radiation. In the measurements designated "through air," no absorbing medium was introduced in the path of the beam between the lamp and the balance except the glass lenses and plates already mentioned. In the measurements "through red glass," a plate of ruby glass was put in the path of the beam between L_2 and d_3 (Fig. 2). For the observations "through water cell," a 9 mm layer of distilled water in a glass cell was placed in the path of the beam at the same point.

The separate observations entering into a single series of ballistic measurements and their treatment will appear from Table II, which is copied direct from the laboratory notebook and represents an average ballistic series. The designations

EVC_s, WVD_s, EVD_g, WVC_g mean that the vane C in the first case was on the east side of the rotation axis with its silver face toward the light. The subscript g signifies that the glass face of the vane was toward the light. The second column of the table gives the zero reading of the balance before opening the shutter; the third, the end of the swing produced by a six-second exposure; the fourth, the deflection of the balance; the fifth, the ballistic deflection of the lamp galvanometer G_2. Columns six and seven give the balance deflection reduced to standard lamp.

The results of all the ballistic pressure measurements "through air" are collected in Table II. In the fourth and fifth columns two values are given for the constant of the lamp galvanometer G_2, since reversing the magnet on the balance bell-jar to reverse the suspension within affected the constant of the galvanometer slightly, the values for the silver and glass faces forward were never the same. The subscripts show to which series, silver or glass, the constant belongs. The values of the lever-arm l of the balance, in the sixth column, are obtained by measuring the distance between the centers of the images when on the east and west vanes (by the dividing engine T_2, Fig. 2) and dividing by two. The columns headed $\frac{C_s + D_s}{2} = P_s$ and $\frac{C_g + D_g}{2} = P_g$ are the average moments due to pressures for the silver and glass sides of the vanes respectively toward the light. The next two columns contain these moments corrected for a period of 24 seconds of the torsion balance. The columns headed $\frac{P_s \times G_s}{l}$ and $\frac{P_g \times G_g}{l}$ are the corresponding forces reduced to standard sensitiveness, $G = 1000$. The final column contains the averages of the two columns which precede it. Table III exhibits corresponding data for "red glass" and "water cell." The air pressure, period of the balance, lever arm and galvanometer constants are those given in Table II for the same date.

In these ballistic measurements the lamp reading was the throw due to an exposure of the light upon the bolometer for six seconds, but in the energy measurements the lamp reading was a stationary deflection due to prolonged exposure. To bring the pressure values into comparison with the energy meas-

TABLE I.

AUGUST 28. LIGHT PRESSURE. BALLISTIC MEASUREMENTS. AIR.

Surface	Zero	Throw	Deflection	Lamp	Deflection (Lamp 100)	
					E. V.	W. V.
			mm	mm	mm	mm
E V C_s....	281.4	248.5	32.9	164.3	20.0	
W V D_s...	281.5	313.9	32.4	164.5		19.7
E V C_s....	281.4	249.8	31.6	157.9	20.0	
W V D_s...	281.5	310.5	29.0	147.0		19.8
E V C_s....	281.5	252.6	28.9	144.8	20.0	
W V D_s...	281.5	309.6	28.1	141.8		19.8
E V C_s....	281.5	252.9	28.6	143.5	19.9	
W V D_s...	281.5	309.3	27.8	140.4		19.8
				Average.....	19.97	19.77

Average, $\frac{C_s + D_s}{2} = 19.87$

MAGNET REVERSED.

E V D_g....	280.1	246.0	34.1	180.4	18.92	
W V C_g....	280.0	317.8	37.8	187.3		20.20
E V D_g....	279.8	247.2	32.6	170.8	19.20	
W V C_g....	279.4	313.7	34.3	169.4		20.25
E V D_g....	279.1	248.9	30.2	161.1	18.80	
W V C_g....	279.0	311.9	32.9	161.6		20.35
E V D_g....	279.0	249.1	30.0	158.9	18.90	
W V C_g....	278.9	311.2	33.2	164.4		20.20
				Average.....	18.97	20.25

Average, $\frac{C_g + D_g}{2} = 19.61$

TABLE II.

RADIATION PRESSURE. BALLISTIC MEASUREMENTS, THROUGH AIR.

Date	Air Pressure in mm of Hg.	Balance Period T	Sens. of Galvanometer G_s (Silver)	Sens. of Galvanometer G_g (Glass)	l = Lever Arm cm	$\frac{C_s + D_s}{2} = P_s$	$\frac{C_g \times D_g}{2} = P_g$	P_s corrected for $T = 24''$	P_g corrected for $T = 24''$	$\frac{P_s \times G_s}{l}$	$\frac{P_g \times G_g}{l}$	Average
June 19.....	32.5	23.75	[734]		0.814	Aver.= 18.88		Aver.= 18.73		Aver.= 16.89		16.89
20.....	32.5	23.75	756.	768	0.814	19.67	16.94	19.51	16.81	18.12	15.86	17.00
23.....	37.0	23.75	700	716	0.814							
July 23.....	16.0	23.75	682	707	0.831	21.16	20.42	21.00	20.26	17.25	17.25	17.25
25.....	16.6	23.75	684	684	0.815							
26.....	16.0	23.75	720	710	0.815	19.34	19.98	19.18	19.82	16.93	17.28	17.10
August 27.....	16.8	23.82	724	710	0.823	20.16	19.40	20.00	19.25	17.60	16.61	17.10
28.....	15.7	23.82	721	716	0.824	19.87	19.61	19.73	19.48	17.26	16.97	17.10
29.....	13.7	23.82	712	701	0.824	19.68	20.07	19.53	19.92	16.90	16.97	16.94
31.....	14.0	24.00	718	713	0.810	18.55	18.94	18.55	18.94	16.44	16.60	16.52
September 1.....	16.6	24.00	692	672	0.808	19.14	20.17	19.14	20.17	16.40	16.78	16.59
20.....	16.4	23.78	670	676	0.812	20.96	20.02	20.81	19.87	17.17	16.54	16.86
23.....	16.4	23.78	666	684	0.816	21.32	20.27	21.16	20.12	17.27	16.87	17.07
24.....	16.2	23.78	667	669	0.816	20.76	19.80	20.60	19.65	16.84	16.11	16.47
						Average.....		17.11	16.71	16.91 ± 0.053		

urements it is necessary to reduce the average of the quantities in the last column to pressures in dynes by multiplying by 0.363×10^{-5}, the torsion coefficient of the quartz fiber, and to reduce not only to a static deflection of the torsion balance but also to a static deflection of the lamp galvanometer G_2. The ratio of a ballistic to a static deflection of the galvanometer G_2 was obtained from a long series of lamp exposures. This ratio was found "through air" to be $= 1.55$; "through red glass" $= 1.535$; "through water cell" $= 1.502$. These differences are probably due not solely to the damping constant of the galvanometer but to the peculiar manner in which the bolometer was warmed up to its stationary conditions by the beam from the lamp. Applying these reduction factors to the averages in Tables II and III, we obtain the following results. The pressure of the standard light beam which has passed

(*a*) through air $= 16.91 \times \frac{1.55}{1.357} \times 0.363 \times 10^{-5} =$
$(7.01 \pm 0.023) \times 10^{-5}$ dynes ;

(*b*) through red glass $= 16.91 \times \frac{1.535}{1.357} \times 0.363 \times 10^{-5} =$
$(6.94 \pm 0.024) \times 10^{-5}$ dynes ;

(*c*) through water cell $= 16.20 \times \frac{1.502}{1.357} \times 0.363 \times 10^{-5} =$
$(6.52 \pm 0.028) \times 10^{-5}$ dynes .

TABLE III.

RADIATION PRESSURE. BALLISTIC MEASUREMENTS.

	Through Water Cell.						
Date	$\frac{C_s + D_s}{2}$	$\frac{C_g + D_g}{2}$	P_s corrected for $T=24°$	P_g corrected for $T=24°$	$\frac{P_s \times G_s}{l}$	$\frac{P_g \times G_g}{l}$	P Average
June 20	18.62	17.10	18.46	16.96	17.14	16.00	16.57
July 25	19.00	20.10	18.85	19.94	15.82	16.74	16.28
26	18.03	19.39	17.89	19.33	15.80	16.84	16.32
August 27	18.63	18.66	18.50	18.53	16.29	15.99	16.14
29	18.25	19.02	18.10	18.87	15.68	16.06	15.87
September 20	20.39	19.14	20.23	19.00	16.69	15.82	16.25
23	20.21	19.51	20.05	19.36	16.37	16.23	16.30
24	19.84	18.91	19.69	18.77	16.10	15.40	15.70
Average	.....	.....	.....	.....	16.24	16.15	16.20 ±0.066

TABLE III—*Continued.*

THROUGH RED GLASS.

June 23	19.99	18.40	19.83	18.26	17.05	16.06	16.56
July 25	20.70	20.94	20.54	20.77	17.24	17.43	17.33
August 27	19.97	19.25	19.82	19.10	17.46	16.46	16.96
28	19.99	19.42	19.84	19.28	17.36	16.75	17.05
29	19.99	19.92	19.84	19.77	17.14	16.82	16.98
31	18.98	19.14	18.98	19.14	16.82	16.84	16.83
September 20	21.00	19.97	20.83	19.82	17.19	16.50	16.84
23	21.48	20.34	21.31	20.18	17.39	16.92	17.15
24	21.00	19.68	20.83	19.53	17.03	16.03	16.53
Average	.....	.....	.....	.....	17.18	16.65	16.91 ±0.051

THE ENERGY MEASUREMENTS.

Before rejecting the bolometer method used in the preliminary measurement of energy, a second bolometer of slightly different construction was tried; but the lack of uniformity of resistance, already mentioned, made its indications too uncertain for the present work. The radiant intensity of the beam used in the later experiments was determined by directing it upon the blackened face of a silver disk, weighing 4.80 grams of 13.3 mm diameter and of 3.58 mm thickness, and by measuring its rate of temperature rise as it passed through the temperature of its surroundings. The disk was obtained from Messrs. Tiffany & Co., and was said by them to be 99.8 per cent. fine silver. Two holes were bored through parallel diameters of the disk, one-fourth of the thickness of the disk from either face. Two iron-constantan thermo-junctions, made by soldering 0.1 mm wires of the two metals, were drawn through the holes into the center of the disk. To insulate the wires from the disk, fine drawn glass tubes were slipped over them and thrust into the holes, leaving less than 2 mm bare wire on either side of the junctions. The wires were sealed into the tubes, and the tubes into the disk by solid shellac. The tubes projected 15 mm or more from the disk and were bent upward in planes parallel to the faces of the disk. The general arrangement will be seen in Fig. 5. The disk was suspended by the four wires some distance below a small flat wooden box. On the box was fastened a calorimeter can swathed in cotton and filled with kerosene in which the con-

stant thermo-junctions were immersed. Copper wires soldered to the two ends of the thermo-electric series were brought out of the calorimeter, and the circuit was closed through 1,000 ohms in series with the 500 ohms resistance of galvanometer G_1. The thermo-junctions in the disk were in series, and as each junction was midway between the central plane of the disk and either face, it was assumed that when the disk was slowly warmed by heating one face the electro-motive forces obtained corresponded to the mean temperature of the disk. One face of the disk was blackened by spraying it with powdered lampblack in alcohol containing a trace of shellac. This method was suggested by Professor G. E. Hale and gives very fine and uniform dead black coatings not inferior to good smoke deposits.

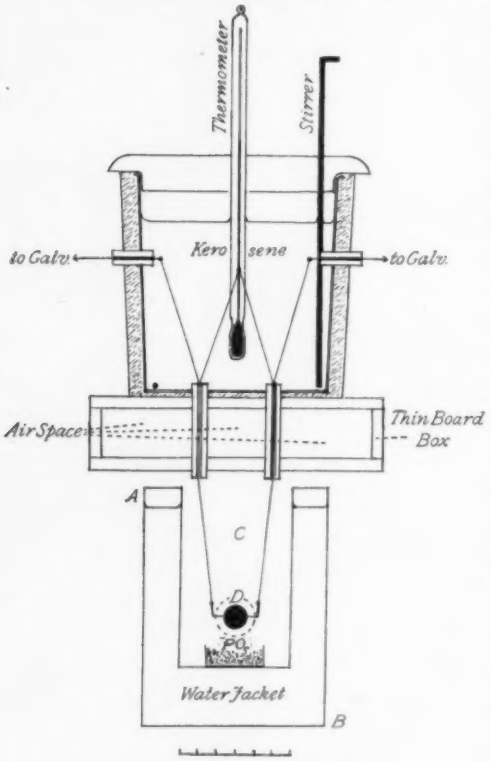


FIG. 5.

For the energy measurements the bell-jar and the torsion balance were removed from the platform P (Fig. 1) and a double-walled copper vessel, AB (Fig. 5), which served as a water jacket surrounding a small air chamber C, was mounted in the same place. A tube 2 cm in diameter was soldered into the front face of the jacket to admit the light beam into the chamber C. This opening was covered by a piece of plate glass similar to the plates forming the larger windows in the bell-jar.

The needle system in G_1, a four-coil du Bois-Rubens galvanometer, was suspended in a strong magnetic field so that its period was about four seconds. The system was heavily damped by a mica air-fan of large surface. The disk junctions and

galvanometer responded quickly to the radiation, as was shown by the reversal of motion of the magnet system 1.2 seconds after the light was cut off from the disk, when the latter was a few degrees above the temperature of the room.

The disk was calibrated for temperature in terms of the deflection for a definite sensitiveness of the galvanometer G_1. For this purpose the disk was immersed in a kerosene bath and the galvanometer deflection measured for two different temperatures of the disk. One of these was about 18° C. above the comparatively steady temperature of the room, or calorimeter containing the standard temperature junctions (see Fig. 5), and the other about the same number of degrees below the room temperature. These two temperatures were measured by a Fuess Standard Thermometer divided into tenths of a degree and calibrated at the *Reichsanstalt*. Two calibrations of the silver disk were made some days apart. One of these series appears in full in Table IV. The first three columns of the table give the zero,

TABLE IV.

CALIBRATION OF SILVER DISK.

Cold Bath.								
G_1 Readings			Disk $T_1°$	Room cal. $T_2°$	Deflection of G_1	Means of Alternate Deflections	G_1 Means	$T_2°-T_1°$
Reversed	Zero	Direct						
	221.2							
	221.0	35.2	1°.58	20°.05	185.8			
	220.9							
402.0	*221.0*		1.60	20.07	181.0	185.7	183.4	18.47
	221.2							
	221.2	35.7	1.57	20.10	185.5	181.3	183.4	18.53
	221.2							
403.1	*221.5*		1.56	20.14	181.6	185.8	183.7	18.58
	221.9							
	222.0	35.9	1.54	20.16	186.1	182.2	184.1	18.62
	222.1							
405.0	*222.2*		1.52	20.20	182.8	186.3	184.5	18.68
	222.4							
	222.7	36.2	1.57	20.22	186.5	182.7	184.6	18.65
	223.0							
405.8	*223.1*		1.60	20.26	182.7	186.7	184.7	18.66
	223.2							
	223.3	36.3	1.59	20.30	187.0			
	223.5						184.0	18°.60
	Correction to $T_1 = 0°.00$.							

TABLE IV—*Continued.*

				Warm Bath.				
	217.3							
	218.6	434.2	41°45	20°40	215.6			
	219.9							
2.0	*220.5*		41.35	20.42	218.5	213.7	216.1	20.93
	221.1							
	222.4	434.2	41.25	20.44	211.8	216.4	214.1	20.81
	223.7							
10.0	*224.4*		41.08	20.50	214.4	209.1	211.7	20.58
	225.1							
	225.7	432.1	40.90	20.55	206.4	212.4	209.4	20.35
	226.3							
16.3	*226.7*		40.80	20.60	210 4	204.8	207.6	20.20
	227.2							
	227.8	431.0	40.67	20.61	203.2	208.5	205.8	20.07
	228.4							
21.8	*228.5*		40.55	20.63	206.7	201.8	204.2	19.92
	228.7							
	229.0	429.4	40.43	20.65	200.4			
	229.3						209.8	20°41
	Correction to $T_1 = 0°10$.						Corrected, 20.51	

direct, and reversed reading of the galvanometer G_1. The fourth column gives the temperature of the bath in which the disk was immersed, and the fifth, that of the constant temperature calorimeter. The sixth column gives the deflections of G_1. The seventh column the means of the alternate deflections. The eighth, the mean of the two columns preceding it. The last column gives the difference in temperature between the two calorimeters in degrees C. For the total temperature range in the table, 39°.11, the deflection of G_1 was 393.8 scale divisions for a sensitiveness of $G_1 = 996$. A range of one degree would thus give a deflection of 10.03 divisions for a sensitiveness of $G_1 = 1000$. The mean of two separate calibrations was 9.96 scale divisions for one degree temperature difference.

Before beginning a series of intensity measurements the disk was suspended in an air-chamber containing phosphoric anhydride and surrounded by a jacket of ice and salt. The disk was thus lowered to a temperature of about zero degrees and was then quickly transferred to the chamber C (Fig. 5), and the beam was directed upon it. When its temperature had risen to

within five or six degrees of that of the chamber C, galvanometer readings were made at intervals of five seconds until the disk was heated to a temperature several degrees above its surroundings. The temperature of the chamber C was determined by removing the disk and cooling it to a point near the room temperature, then replacing it and observing its rate of temperature change for several minutes.

The notebook record of one series of observations showing the heating of the disk by the light beam is given in full in Table V. It will be seen from the table that the temperature of the disk passed that of the chamber thirty seconds after the beginning of the series. The readings of G_1 at equal time intervals on either side of the zero are on horizontal lines. The last column of the table contains the rate at which the galvanometer deflection was changing when the disk and its surroundings were at the same temperature.

Energy series were made "through air," "through red glass," and "through water cell," as in the pressure measurements. During the experiment the black coatings were frequently cleaned off from the disk and new ones deposited. The final result therefore does not correspond to an individual, but to an average coating.

To correct for any inequality between the two disk thermojunctions or any lack of symmetry in their positions, referred to the central plane of the disk, which might prevent the mean temperature of the two junctions from representing the mean temperature of the mass, series of observations were made on each face of the disks. The black coating was always cleaned off from the face of the disk away from the light. All of the series of energy measurements are gathered together in Tables VI and VII. In the tables, under the head of "through air," the first column contains the observed rate of increase in the galvanometer deflection G_1, when the disk and its surroundings were at the same temperature; the second column, the corresponding mean lamp deflections of galvanometer G_2. The third and fourth columns contain the sensitiveness of galvanometers G_1 and G_2 respectively, and the last column the values of the

TABLE V.

AUGUST 16. ENERGY MEASUREMENTS. THROUGH AIR. SERIES 4.

Zero of galvanometer G_1 (closed circuit) determined by method of cooling = 216.8 = reading at room temperature.

Time	G_1	Time	G_1	ΔG_1	Δt	$\frac{\Delta G_1}{\Delta t}$ (in mm per sec.)
0 secs.	174.5	60 secs.	253.2	78.7	60 secs.	1.312
5 "	182.0	55 "	247.3	65.3	50 "	1.306
10 "	189.0	50 "	241.3	52.3	40 "	1.308
15 "	196.2	45 "	235.2	39.0	30 "	1.300
20 "	203.0	40 "	229.1	26.1	20 "	1.305
25 "	209.7	35 "	222.8	13.1	10 "	1.310
30 "	216.4			Average.....		1.307

The lamp reading (G_2) was 924.

The sensitiveness of G_2 was 667, and of G_1 was 996.

$\frac{\Delta G_1}{\Delta t}$ reduced to standard conditions becomes

$1.307 \times 667 \times 996 \div (924 \times 1000) = 0.943$ mm per sec.

first column reduced to standard lamp and standard sensitiveness of both instruments. The series on the two faces of the disk are recorded and averaged separately, then combined with their probable errors in the general average at the end of Table VII.

Tables VI and VII give the following results. The average increase in the reading of G_1 for standard conditions is 0.966 mm per second. From the thermal calibration, a deflection of 9.96 divisions corresponds to a temperature difference of 1° C. Consequently the rise in temperature of the silver disk per second when the light passed:

(*a*) through air = $0.966 \div 9.96 = (0.^{\circ}0970 \pm 0.^{\circ}00034)$ C.;

(*b*) through red glass = $0.942 \div 9.96 = (0.^{\circ}0946 \pm 0.^{\circ}00036)$ C.;

(*c*) through water cell = $0.880 \div 9.96 = (0.^{\circ}0884 \pm 0.^{\circ}00064)$ C.

The mass of the silver disk was 4.80 grams, its specific heat[1] at 18° C. = 0.0556; the mechanical equivalent of heat at 18° C.

[1] U. BEHN, *Ann. der Phys.*, **4**, 266, 1900.

TABLE VI.

FRONT FACE.

Date	Through Air					Through Red Glass			Through Water Cell		
	$\frac{\delta G_1}{\delta t}$	G_2 (Lamp)	S_1	S_2	$\frac{\delta G_1}{\delta t}$ Reduced to Stan.	$\frac{\delta G_1}{\delta t}$	G_2	$\frac{\delta G_1}{\delta t}$ Reduced to Stan.	$\frac{\delta G_1}{\delta t}$	G_2	$\frac{\delta G_1}{\delta t}$ Reduced
August 10..	1.387	980	990	689	0.965				0.437	345	0.864
10..	1.263	920	990	689	0.936				0.400	311	0.877
10..									0.369	279	0.902
11..	1.244	866	986	701	0.992	0.750	546	0.950	0.412	315	0.905
11..	1.455	1010	986	701	0.995	0.750	546	0.950	0.510	382	0.922
11..	1.505	1047	986	701	0.994				0.516	381	0.935
16..	1.447	1022	996	669	0.942	0.736	529	0.927	0.416	327	0.873
16..	1.284	886	996	669	0.966	0.740	527	0.936	0.451	352	0.853
16..	1.316	925	996	669	0.948	0.797	550	0.965	0.502	382	0.875
16..	1.307	924	996	669	0.943						
18..	1.598	1110	995	667	0.955	0.738	515	0.952	0.449	333	0.895
18..	1.550	1047	995	667	0.984	0.732	518	0.940	0.445	342	0.865
18..	1.548	1031	995	667	0.995	0.730	518	0.938	0.451	346	0.867
18..	1.410	957	995	667	0.977						
18..	1.330	898	995	667	0.983						
19..	1.241	862	1001	675	0.975	0.760	532	0.965	0.451	343	0.892
19..	1.360	934	1001	675	0.985	0.728	512	0.960	0.452	338	0.904
19..	1.324	905	1001	675	0.990	0.738	525	0.950	0.466	351	0.898
19..	1.364	934	1001	675	0.988						
					Average..... 0.973 ±0.003			Average..... 0.948 ±0.002			Average..... 0.888 ±0.004

TABLE VII.

REAR FACE.

Date	Through Air					Through Red Glass			Through Water Cell		
	$\frac{\delta G_1}{\delta t}$	G_2 (Lamp)	S_1	S_2	$\frac{\delta G_1}{\delta t}$ Reduced to Stan.	$\frac{\delta G_1}{\delta t}$	G_2	$\frac{\delta G_1}{\delta t}$ Reduced	$\frac{\delta G_1}{\delta t}$	G_2	$\frac{\delta G_1}{\delta t}$ Reduced
August 12..	1.374	960	991	684	0.970	0.808	578	0.949	0.495	370	0.906
12..	1.331	932	991	684	0.968	0.740	536	0.935	0.434	330	0.919
12..	1.284	900	991	684	0.967	0.765	542	0.957	0.489	371	0.895
15..	1.428	992	996	670	0.960	0.703	506	0.926	0.490	368	0.890
15..	1.428	984	996	670	0.968	0.742	526	0.941	0.466	352	0.885
15..	1.531	1068	996	670	0.962	0.765	551	0.926	0.440	327	0.873
20..	1.477	1047	996	685	0.961	0.703	522	0.918	0.458	375	0.833
20..	1.520	1090	996	685	0.951	0.760	537	0.965	0.497	400	0.848
20..	1.576	1130	996	685	0.951	0.781	570	0.935	0.507	408	0.848
20..	1.568	1124	996	685	0.950						
21..	1.783	1224	995	668	0.970	0.846	604	0.932	0.503	393	0.852
21..	1.773	1232	995	668	0.957	0.790	575	0.915	0.481	377	0.850
21..	1.705	1190	995	668	0.953	0.803	575	0.930	0.483	373	0.862
21..	1.452	1019	995	668	0.948						
					Average..... 0.960 ±0.0014			Average..... 0.936 ±0.003			Average..... 0.872 ±0.005
					Average of front and rear face, 0.966 ±0.0034			0.942±0.0036			0.880±0.0064

$= 4.272 \times 10^7$ ergs.[1] Consequently the energy of the standard radiation is

(a) through air, $0.0970 \times 4.80 \times 0.0556 \times 4.272 \times 10^7$
or $E_a = (1.108 \pm 0.004) \times 10^6$ ergs per second.
(b) through red glass, $E_g = (1.078 \pm 0.004) \times 10^6$ ergs per second.
(c) through water cell, $E_w = (1.008 \pm 0.007) \times 10^6$ ergs per second.

REFLECTING POWER OF THE SURFACES USED.

According to Maxwell and Bartoli, the pressure in dynes per square centimeter for normal incidence is equal to the energy in ergs in unit volume of the medium. The energy in unit volume is made up of both the direct and reflected beams. If E is the intensity of the incident beam and ρ the reflection coefficient, the pressure $p = \frac{E(1+\rho)}{V}$, where V is the velocity of light. The methods for measuring p and E have already been described. The determination of ρ for both sides of the vanes C and D was made as follows. The supports of the torsion balance were replaced by the divided circular plate A (Fig. 6), of a force table which could be rotated about a central, vertical axis. The rod about which the plate turned passed up through the plate and at its top the mirror holder bb was fastened. The vanes were freshly silvered and mounted on a plate-glass carrier aa, which was held by a clamp against the back face of bb. The beam was directed on the vanes by the lens L_3 (Figs. 2 and 6) exactly as it had been in the pressure observations. After reflection from the vane the beam fell on a concave mirror M which projected an image of the vane upon a simple sheet bolometer B, forming the unknown resistance of a post-office box bridge. The current was supplied from storage cells and the galvanometer was the same used in the energy determinations but fitted with low resistance coils. The bolometer was covered by the bell-jar used earlier. The mirror M, the bell-jar, and bolometer were attached to the plate of the force table. The full line diagram shows the arrangement for reflection. The dotted figure shows the position for a measurement of the direct beam. All measurements of direct reflection were made for an angle of incidence of $12^\circ.5$.

[1] Mean of Rowland's and Griffith's values. *Phil. Trans.*, **5**, 184, 496, 1893.

The method of observing will be seen from the notebook record of a single series of measurements given in Table VIII. In the table, D and R indicate direct and reflected beams, respectively. The first and second columns contain the zero points and end of swings of the galvanometer G_1, and the third column, the deflection. The remaining columns, in order, contain the lamp galvanometer deflection; the deflection of G_1 reduced to constant lamp; the means of each pair of D and R values; the means of alternate readings; and the final column, the quotients of the two preceding columns which are the reflection coefficients sought. In all, three series of measurements were made on the silver, and two series on the glass-silver faces of each vane. To get average coefficients which would represent the range of condition of the mirrors during the pressure measurements, the vanes were cleaned and new silver coatings deposited between each two series on the same vane. The reflection coefficients are collected in Table IX. For each surface studied the diffused reflection for a beam which had traversed air was determined by setting the mirror holder for normal incidence. The diffuse energy reflected at an angle of 25° falling on the full aperture of the mirror M was measured, and the total diffuse energy for the hemisphere computed on the basis of the cosine law. It may be shown that of the diffuse reflection, two-thirds is effective as light pressure. This increases the air-silver reflection coefficients by 0.9 per cent. and the glass-silver

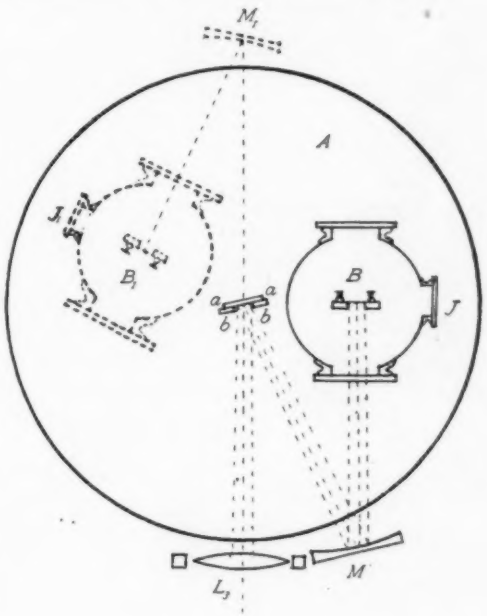


FIG. 6.

TABLE VIII.

OCTOBER 31, 1902. REFLECTION COEFFICIENT OF D_g. AIR.

	G_1 Zero	G_1 Turning Point	Deflection G_1	Lamp	G_1 Reduced to Standard	Averages	Alternate Averages	Reflection Coefficient
R	350.0.....	159.5	190.5	132.6	143.8	142.5		
	349.0.....	152.0	197.0	139.3	141.3			
D	349.5.....	100.5	249.0	136.8	182.1	182.5	142.0	0.779
	350.0.....	111.5	238.5	130.5	183.0			
R	346.0.....	177.0	169.0	119.3	141.2	141.5	182.5	.775
	347.0.....	171.0	176.0	124.4	141.7			
D	348.5.....	123.0	225.5	124.0	181.8	182.4	141.1	.773
	348.5.....	120.0	228.5	125.0	183.0			
R	345.0.....	172.0	173.0	122.6	141.0	140.6	182.7	.770
	345.0.....	171.0	174.0	124.0	140.3			
D	346.0.....	132.0	214.0	115.5?		183.0	141.2	.773
	346.0.....	124.0	221.0	120.7	183.0			
R	344.0.....	173.0	171.0	120.7	141.8	141.7	182.1	.778
	344.5.....	171.0	173.5	122.6	141.6			
D	346.0.....	119.0	227.0	125.3	181.0	181.2	141.6	.781
	346.0.....	117.5	228.5	126.0	181.3			
R	342.0.....	174.0	168.0	118.0	142.3	141.5	181.8	.780
	342.0.....	170.5	171.5	122.0	140.8			
D	347.0.....	130.0	217.0	119.0	182.3	182.5	141.4	.775
	347.0.....	134.0	213.0	116.7	182.7			
R	341.5.....	174.5	167.0	118.0	141.3	141.2		
	341.0.....	173.0	168.0	119.0	141.1			

Average 0.776

TABLE IX.

REFLECTION COEFFICIENTS IN PERCENTAGES.

	C_s				C_g			
	Through Air	Red Glass	Water	Diffuse	Through air	Red Glass	Water	Diffuse
	92.8	94.5	88.9	0.98	77 8	75.9	80.8	
	89.8	90.8	86.0	0.92	77.6	76.6	80.0	1.6
	90.8			1.23				
Average..	91.1	92.7	87.5	1.04	77.7	76.3	80.4	1.6
	D_s				D_g			
	95.0	96.3	91.5	2.2	77.6	76.5	81.0	2.8
	92.0	94.0	90.4		76.7	75.2	79.7	2.2
	94.8	95.0	92.3	0.8				
Average..	93.9	95.1	91.4	1.5	77.2	75.9	80.4	2.5

TABLE IX—*Continued.*

AVERAGE REFLECTION.

Air-Silver				Glass-Silver			
92.5	93.9	89.5	1.3	77.5	76.1	80.4	2.0

CORRECTED REFLECTION COEFFICIENTS.

92.0	93.4	89.0	77.6	76.2	80.5	

Average Coefficients through Air, *84.8;* Red Glass, *84.8;* Water, *84.8.*

values by 1.3 per cent. The small glass rod *d* (Fig. 1), not present in the reflection measurements, decreased the reflecting area of the silvered surfaces in the pressure measurements by 1.54 per cent. The air-silver values are thus decreased by $0.92 \times 1.54 = 1.4$ per cent., and the glass-silver values by $0.78 \times 1.54 = 1.2$ per cent. The application of these two corrections gives the final corrected coefficients in Table IX. The diffuse reflection of black coatings deposited by the method used in blackening the silver disk was measured and computed in the same manner as the diffused reflection from the vanes *C* and *D*. The agreement found by Ångström[1] between the diffuse reflection of matte surfaces for normal incidence and the cosine law was abundantly close for the present purpose. Five determinations of this reflection were made under different conditions and with different coatings. The values in percentages of the incident beam were 4.4 per cent., 4.5 per cent., 4.2 per cent., 4.6 per cent., and 5.2 per cent.; average, 4.6 per cent. Thus only 95.4 per cent. of the incident beam was absorbed by the black coating on the silver disk in producing the temperature increase observed. Hence the true energy of the beam is equal to the observed energy divided by 0.954.

The silver disk, diameter 13.3 mm, used in the energy measurements, received long waves and scattered radiation which passed round and through the light pressure vanes of diameter 12.8 mm. This amount was experimentally determined for both thin and thick silver coatings in order to approximate to the

[1] K. Ångström, *Wied. Ann.*, **26**, 271, 1885.

average condition of the coatings in the light pressure measurements, and it was found to average (a) through air, 1.40 per cent.; (b) through red glass, 1.44 per cent.; (c) through water, 0.46 per cent. On this account the energy E of the standard radiation must be reduced by the above percentages.[1] Applying these corrections and the corrections due to the diffused radiation from the black coating on the silver disk, the energy of the standard radiation becomes

(a) through air, $E_a \times \frac{0.986}{0.954}$;

(b) through red glass, $E_g \times \frac{0.986}{0.954}$;

(c) through water, $E_w \times \frac{0.995}{0.954}$;

Hence the pressure produced by standard radiation, calculated by Maxwell's formula, $p = \frac{E(1+\rho)}{3 \times 10^{10}}$, since $\rho = 0.848$, becomes

(a) through air
$$= E_a \times \frac{1.848}{3 \times 10^{10}} \times \frac{0.986}{0.954}$$
$$= 1.108 \times \frac{1.848}{3 \times 10^{10}} \times \frac{0.986}{0.954} \times 10^6 \text{ dynes}$$
$$= (7.05 \pm 0.03) \times 10^{-5} \text{ dynes} ;$$

(b) through red glass
$$= E_g \times \frac{1.848}{3 \times 10^{10}} \times \frac{0.986}{0.954}$$
$$= 1.078 \times \frac{1.848}{3 \times 10^{10}} \times \frac{0.986}{0.954} \times 10^6 \text{ dynes}$$
$$= (6.86 \pm 0.03) \times 10^{-5} \text{ dynes} ;$$

(c) through water
$$= E_w \times \frac{1.848}{3 \times 10^{10}} \times \frac{0.995}{0.954}$$
$$= 1.008 \times \frac{1.848}{3 \times 10^{10}} \times \frac{0.995}{0.954} \times 10^6 \text{ dynes}$$
$$= (6.48 \pm 0.04) \times 10^{-5} \text{ dynes.}$$

[1] As the average pitch of the cone of the incident beam was about one part in forty, no correction need be applied for inclination. Furthermore, the inside of the bell-jar was blackened and the zero of the balance was so chosen that energy reflected from the window admitting the beam could produce no pressure effects.

A comparison of observed and computed pressures follows:

	Observed Values in 10^{-5} Dynes	Computed Values in 10^{-5} Dynes	Obs.-Comp. in Percentages
Through air.....	$p=7.01\pm0.02$ [1]	7.05 ± 0.03	-0.6
Through red glass ...	$p=6.94\pm0.02$	6.86 ± 0.03	$+1.1$
Through water	$p=6.52\pm0.03$	6.48 ± 0.04	-0.6

An estimate of the approximate magnitude of the gas action, not eliminated by the ballistic method of observation, may be reached from the following considerations.

When radiation falls upon a vane of the torsion balance, part of it is absorbed by the silver surface. From the amounts directly and diffusely reflected, as given in Table IX, the amount transmitted by the average surface (experimentally determined but not given in Table IX), the effect of the glass rod and the reflection coefficient of the glass surface, it was found that, when the silver side of the vane was toward the radiation source, the absorption coefficient for radiation through air was 6 per cent., and when the glass surface was forward, it was 18 per cent.

The total force acting on the vane is made up of two parts, that due to radiation pressure and that due to gas action. Let F_r be the force due to the first cause, assuming that all the radiation is absorbed, and F_g the effect due to the second, on the same condition. Then the total effect, when the silver side of the vane is forward and the radiation is "through air," is $1.92\,F_r+0.06\,F_g$. When the glass side is forward the total effect is $1.776\,F_r-0.18\,F_g$. Making these expressions equal to the reduced deflections (Table II, columns 11 and 12) on the silver and glass surfaces respectively, we have two equations by means

[1] The pressure and energy measurements for the three different wave groups through air, red glass, and water cell, constitute three independent experiments. In the values for pressure, 7.01, 6.94, and 6.52 in the three cases are only accidentally related. The difference arises from the different reflecting power of the 45° glass plate (Fig. 2) for the different beams and from the fact that the indications of the lamp galvanometer G_2 connected with bolometer R, were probably not strictly proportional to energy for throws differing as widely as 33, 60, and 100, which, roughly, were the relative intensities of the beams through water cell, red glass, and air. The function of the lamp bolometer and galvanometer was purely to keep a check on the small variations of the lamp, which rarely fluctuated more than 10 per cent. on either side of the mean value.

of which the values of F_r and F_g may be obtained. Hence the effect due to gas action on each face of the vane is approximately determinate, as is also the part ($0.06\,F_g$) not eliminated when we average the two columns to obtain column 13.

Applying this method to all the results of Table II (with the exception of those results taken with poor mirrors as shown by our notes), the gas action present in the ballistic deflections "through air" is 0.8 per cent. Applying the corresponding data and equations to Table III, the gas action present in the red glass values is 1.1 per cent. and in the water cell values, 0.3 per cent. The sign of F_g comes out negative, which means that the gas action was suction.

This reasoning assumes that the glass faces of the vanes during the six seconds exposure are not warmed by absorption nor by the conduction of heat through the thin glass from the silver coating. The effect of any such absorption or conduction would be to diminish the computed gas action. As estimated from the static observations, the gas action in the ballistic measurements is comparable in magnitude with the computed values obtained above, and of the same sign. Both results show that the uneliminated gas action by the most liberal estimate cannot have exceeded 1 per cent. of the radiation pressure. Because of its smallness and indefiniteness no correction for gas action has been made to the final pressure values. If corrections were applied, its effect would be to reduce slightly the observed pressures.

Aside from the measurements of pressure and energy for which the probable errors are given, the percentage accuracies in the other measurements entering into the computations, and their effects upon the final result follow:

1. Quantities which affect individual series:

(*a*) Pressure values—

Period of balance	T,	accurate to 0.2 %;	effect on result	0.0 %
Lever arm of balance	L,	" 0.1 %;	" "	0.0 %
Constant of galv'meter	G_2,	" 0.5 %;	" "	0.0 %
Estimate of possible error due to changing ratio of period of G_2 to length of exposure of bolometer		" 0.4 %;	" "	0.1 %

(*b*) Energy values—

Constant of galv'meter G_1, accurate to 0.1 %; effect on result 0.0 %

" " G_2, " 0.5 %; " " 0.0 %

2. Quantities which affect final averages:

(*a*) Pressure values—

Torsion of fiber,	accurate to	0.2 %	: effect on result		0.2 %
Reducing factor, 1.357	"	0.1 %	; "	"	0.1 %
Reducing factor, 1.550 for G_2	"	0.2 %	; "	"	0.2 %
Reflection of surfaces of vanes	"	0.4 %	; "	"	0.2 %

(*b*) Energy values—

Mass of silver disk	"	0.1 %	; "	"	0.1 %
Thermal calibration of disk	"	0.5 %	; "	"	0.5 %
Diffuse reflection black coating	"	5.0 %	; "	"	0.1 %

From the agreement within the probable error of the air, red glass, and water values with the theory, it appears that the radiation pressure depends only upon the intensity of the radiation and is independent of the wave-length.

The Maxwell-Bartoli theory is thus quantitatively confirmed within the probable errors of observation.

WILDER LABORATORY, DARTMOUTH COLLEGE,
Hanover, N. H., February 1903.

THE APPLICATION OF RADIATION PRESSURE TO COMETARY THEORY.

By E. F. NICHOLS and G. F. HULL.

IN the experiments described in the foregoing paper the close agreement of theory with experiment warrants the rigid application of the radiation pressure theory in the explanation of cosmical phenomena.

In any balancing of radiation pressure against gravitation in comets the size of particles is the determining factor. The repulsion due to radiation pressure depends upon the intensity of the rays, the absorbing and reflecting power of the surface, and the cross-section of the body exposed. Gravitational attraction depends only upon mass, or the product of volume and density. It will be seen, therefore, that for spheres of a given substance the weight at a fixed distance from the Sun will vary with the cube of the radius, while radiation pressure will depend upon the radius squared. The ratio of pressure to weight will thus be inversely as the radius. This relation holds down to the point where the particles become so small that they begin to lose in absorbing and reflecting power through diffraction.

The intensity of the solar radiation and gravitation diminish with distance in accordance with the same law, so that the ratio of pressure to weight is a constant for the same body at all distances from the Sun.

For spheres of the same size, and the same absorbing and reflecting power, the ratio of pressure to gravitation is inversely as the density. The variation of this ratio, as it depends upon size and density, has been used by Lebedew[1] and Arrhenius[2] in the computation of the repulsion upon the finely divided matter of comets' tails, but the limiting value of the ratio for diminishing

[1] *Wied. Ann.*, 45, 292, 1892; also ASTROPHYSICAL JOURNAL, 14, 155, 1902.

[2] *Lehrbuch der kosmischen Physik*, p. 150, Leipzig, 1903.

spheres of the same density due to diffraction first appears in Schwarzschild's paper.[1]

Comet heads.—In the heads of comets the phenomena are most complicated and difficult of explanation, yet it seems worth while to try to gather together a few of the separate causes which may be at work in producing this intricate structure.

The heat received from the Sun by the nucleus of a comet may be spent in three ways: (1) In raising the temperature of the nucleus. As the nucleus is of relatively small mass and probably of low heat conductivity no very considerable quantity of heat is required for this purpose. (2) Heat may be, and doubtless is, used in the vaporization of volatile hydrocarbons and other substances in the nucleus. (3) Large quantities of heat are lost from the nucleus by radiation.

The porous structure of meteorites points to a similar structure in cometary nuclei. The jets from the nucleus outward to the envelope of the head may be formed by the heating of the vaporizable materials in the interior of the nucleus and the consequent shooting out under pressure of a mixture of gases and dust through holes in a loose outer crust. Lack of sufficient means of escape in this way may cause a bursting of the nucleus sometimes observed.

The general upward current of vapors from the nucleus to the envelope, aside from jets, may be due to convection away from the more strongly heated center.[2]

Because of the counter-pressure due to the radiation of the nucleus itself, the rising of even small solid particles from the nucleus to the envelope would not encounter as strong an unbalanced pressure from the solar rays as particles in the tail. For, if all the heat received from the Sun were again radiated from the nucleus on the side toward the Sun, these two counter-radia-

[1] *Sitzungsberichte der math.-phys. Classe der k. b. Akademie der Wissenschaften zu München*, 31, 293, 1901.

[2] Matter in the form of gases and vapors is not subject to radiation pressure, as solid and liquid particles are, because of the minuteness of molecular dimensions. Except in the spectrum regions of characteristic absorption, radiation can, theoretically, exert no pressure whatever upon a gas. Hence gases might rise from the nucleus toward the Sun practically unhindered by radiation pressure.

tion pressures would exactly balance at the surface of the nucleus.[1]

Small particles may also be aided in rising from the nucleus toward the Sun by gas forces. By numerous experiments on larger bodies immersed in a gas and illuminated on one side, it has been shown that they may be either repelled from the light source or drawn to it, depending upon the pressure of the surrounding gas (see curves, in the foregoing paper, p. 329.) If the gas pressure is not too low, particles after leaving the nucleus might first be drawn toward the Sun until a region of higher vacuum was reached in the ascent, and then be repelled.[2]

The brilliant envelope of the head may be regarded as forming at the height where condensation, caused by expansion and cooling, takes place. Here the repelling action of the solar radiation would reach a high value and the particles in the envelope would be driven backward to form the tail.

According to Arrhenius[3] this condensation in the envelope is assisted by the influx of negatively charged nuclei from the Sun, which serve as condensation centers for the ascending vapors. The height above the nucleus of the comet at which this condensation would occur would thus, in some measure, be governed by the supply of negative particles. These would be found in increasing numbers with diminishing distance from the Sun. This action may be responsible for the contraction of the head and envelope as comets approach the Sun.

[1] It is worth noting in this connection that the longer and invisible waves are as effective in producing pressure as the visible radiations, and that these long waves strongly preponderate in the spectra of solid bodies at temperatures low in comparison with the solar temperature.

[2] It is possible also that electrostatic forces may play a small part in the formation of the head from the nucleus. Arrhenius believes the Sun to have a positive electrical charge, due to the fact that it loses more negative electrons by condensation into nuclei and subsequent repulsion by radiation pressure than it does of *positive* electrons which do not as readily serve as centers of condensation. Streams of negatively charged particles would communicate a negative charge to the matter surrounding the comet's nucleus, which would thus be attracted by the Sun. As this attraction would oppose the formation of the tail in the same measure as it assisted that of the head, it cannot be a dominating influence.

[3] *L. c.*, p. 208.

The brilliancy of the envelope may be attributed, in large part, to the fact that bodies of sufficient size to reflect solar rays are first formed out of the vapors of the head in this region. The negative nuclei from the Sun would here experience an obstruction and lose the greater part of their motion by friction. Electrical interchanges and discharges would be more active, and the hydrocarbon spectrum be brighter in the envelope than in other parts of the head.

If the brightness of the head and its envelope depend upon the number of negatively charged nuclei which strike the comet, and if, as Arrhenius maintains, the nuclei move out from the Sun radially and in greatest numbers from regions of greater solar activity, comets crossing the surface defined by solar radii drawn through the Sun-spot belts should show a marked increase in brightness, especially in maximum Sun-spot years. The writers are not aware that any such influence has been looked for in the cases where sudden changes of brightness in comets have been observed.

Comet tails.—The maximum ratio of radiation pressure to gravitation, obtained theoretically by Schwarzschild for sunlight upon opaque reflected spheres of 0.8 density, under the most favorable conditions, was about 20 to 1, if the recent estimates (ranging from 3.5 to 4) of the solar constant were used.

In Bredichin's three types of cometary tails, the highest ratio of attraction to repulsion required is about 18 to 1.[1] The multiple tails observed in such comets as Donati's may thus be satisfactorily explained by the sifting action of radiation pressure in two ways; either by assuming, with Bredichin, that the particles in the different tails are of different densities, but of uniform size, or by assuming uniform density and particles of several different sizes.

While radiation pressure alone thus affords a satisfactory explanation of comets' tails, there is no reason to assume that it is the only cause of the repulsive action observed. There are several ways in which the gases and vapors present in the tail

[1] In comet 1893 II Hussey observed a considerably larger ratio of repulsion to gravitation.

may exert a force upon the small solid or liquid particles which are known to exist there:

1. Small particles, if warmed on one side when surrounded by gases or vapors, even under pressures so low that electrical discharges take place only under relatively high voltages, experience a strong repulsion, similar to that upon a vane of a Crookes radiometer.

2. Occluded gases or volatile materials upon the surface of the particles would be driven off by the Sun's heat on the illuminated sides, and the particles would thus receive a thrust in the direction away from the Sun.

3. If the particles were porous or loosely put together, containing cavities filled with more easily vaporizable substances, the resulting vapors would be shot out upon the hotter sides and the particles driven back by a kind of rocket action.

That these combined gas forces are still large, even in high vacua, will be seen from an actual experiment described later.

If we accept Arrhenius' theory that the solar activity produces numberless negative electrons which serve as condensation points for the vapors surrounding them in the solar atmosphere, and thus form small, negatively charged nuclei, which are driven from the Sun by radiation pressure,[1] these nuclei would exert a battering action upon the particles of the tail. In the last case a strange meeting point is found between the oldest, or Keplerian, and the latest explanation of the solar repulsion of comets' tails.

Finally Professor J. J. Thomson,[2] in investigating the action of electric waves upon charged bodies immersed in the medium, has found that a small repulsive effect may arise from this cause. This repulsive force is entirely distinct from the radiation pressure so far considered, but on the electromagnetic theory of light it may be competent to drive away electrons formed above the photosphere of the Sun, independently of the

[1] The supposed electrical discharges in the tail of a comet which give rise to its gaseous emission spectrum are attributed by Arrhenius to the electrical disturbances caused by the influx of these negative nuclei.

[2] *Phil. Mag.*, **4**, 253, 1902.

sign of the charge and of whether they have formed nuclei by condensation or not.

These last two causes of repulsion are in all probability of very minor importance when compared with radiation pressure, or even with gas action.

Experiment with a laboratory comet's tail.—Some of the above considerations led the writers to try to reproduce, as nearly as possible, in a vacuum tube some of the conditions believed to exist in comets' tails. The result of a hasty computation of the magnitude of the effect which might be expected from radiation pressure provided a suitable dust could be found was most encouraging.

At the outset it was apparent that it would be very difficult to manufacture a powder the grains of which would be sufficiently small, light, and uniform for the purpose; so the spores of a great variety of degraded vegetable forms were examined. Finally a puff ball of the genus *Lycoperdon* was discovered, the spores of which averaged two microns in diameter, and were as nearly spherical and uniform in size as a pile of apples from the same tree. These spores were light, cellular structures filled mainly with oil. They were calcined by heating to redness and all the vaporizable material driven off, leaving only sponge-like charcoal spheres behind. The density of a mass of these spheres (individuals could obviously not be dealt with) was measured and found to be about one-tenth that of water. Making liberal allowances for the spaces between spheres in the pile, the density of a single sphere could not exceed 0.15.[1]

These spores, together with a quantity of emery sand, were placed in a glass tube the form of which was suggested by the hour-glass. Smaller tubes led off from either end. One of these was fused to a good mercury pump of the Geissler type, the other bent down and joined to a small flask containing mercury.

All of the tubes were wrapped with wire gauze and heated to a temperature just below the softening point of glass and the

[1] According to Schwarzschild's formula, the ratio of radiation pressure to solar gravitation for spheres of the size and density of these spores would be about 6 to 1.

pump was worked many hours. When the pump showed no further signs of gas, the mercury in the flask was boiled and mercury vapor driven through the tubes to carry off any permanent gases which the pump alone could not reach. After this had continued for an hour or more the tube system was sealed off from the pump and the mercury flask was surrounded by solid carbon dioxide and ether, and the hour-glass still heated. In this way all of the mercury vapor which could be condensed at a temperature of $-80°$ C. was drawn out of the tubes. After nearly an hour the mercury flask with its frozen contents was sealed off from the hour-glass.

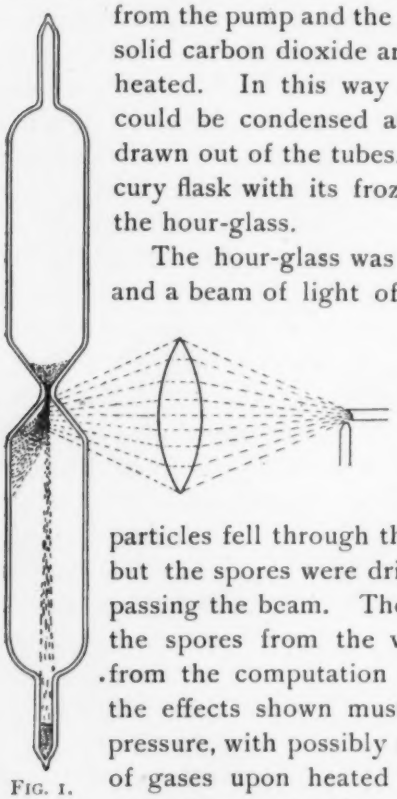


FIG. 1.

The hour-glass was then held in a vertical position and a beam of light of approximately known intensity was directed horizontally on the lower half of the tube just below the neck, Fig. 1. By tapping the tube a fine stream of sand and charcoal puff-ball spores descended. The sand particles fell through the beam, showing no deflection, but the spores were driven from the stream sidewise in passing the beam. The observed angle of deflection of the spores from the vertical was roughly that given from the computation and the observers believed that the effects shown must be due almost entirely to light pressure, with possibly a slight gas action. The action of gases upon heated bodies of this size had, so far as we know, never been studied, but one of the writers[1] had studied the gas action on larger bodies down to a pressure of permanent gases of 0.0005 mm of mercury, as shown by a McCleod gauge, and had observed that for this pressure the gas action had begun to fall off sharply. The pressure of the permanent gases in the hour-glass must have been well below

[1] A result gained in a series of unpublished experiments on gas forces by W. v. ULJANIN and E. F. NICHOLS. See also W. CROOKES, *Phil. Trans.*, p. 300, 1878.

this value and it was thought that nearly all pressure due to vapor had been frozen out.

Later, a review of the preliminary computation was made and an error discovered which had the effect of bringing out the computed light pressure on bodies of this size and density far too large. It was plain, therefore, that the force of deflection due to gas action, probably of the character of rocket action, was at least ten times as large as the effect attributable to radiation pressure. Radiation pressure alone would produce a measurable effect under the conditions of observation, but would have been far less pronounced than the effect obtained.

The experiment had unfortunately to be tried under circumstances much more unfavorable for a pronounced effect of radiation pressure than exist in comets; for the deflection produced by repulsion must be measured in terms of terrestrial gravitation, which is over 1600 times as great as solar gravitation at the distance of the Earth. To approach cometary conditions therefore it would have been necessary to use a light beam 1600 times as intense as sunlight at the Earth. In the experiment, beams from twenty to forty times as intense as sunlight were used.

Because of the meagerness of present knowledge concerning the actual conditions in comets' tails, it is impossible to say how closely the foregoing experiment fulfilled the purpose for which it was tried. It would be difficult to prove from present astronomical data that the hydrocarbon vapors known to exist in comets' tails exert no radiometric repulsion upon the small reflecting particles present. Still more difficult would it be to show that nothing which corresponds to what has been called rocket action occurs. This latter repulsion does not require the presence of any generally diffused atmosphere whatever, but simply that the particles send off gases toward the Sun under the action of the Sun's heat. Thus in passing from the era where no adequate physical causes which would meet the required conditions could be assigned for the repulsion seen in comets, we are now likely to be embarrassed in discriminating between several contributing influences.

The writers hope to repeat the comet's tail experiment using smaller spores, if they can be found, and a tube of the new silica glass which will stand stronger heating during the pumping, and thus make it possible to reach higher vacua.

THE WILDER PHYSICAL LABORATORY,
Dartmouth College, Hanover, N. H., April 1903.

PHOTOGRAPHIC REVERSALS IN SPECTRUM PHOTOGRAPHS.

By R. W. Wood.

The importance of distinguishing between photographic and true reversals of lines in spectrograms has made it seem worth while to investigate with some care the conditions under which reversals due entirely to photographic action can occur. Professor Trowbridge has advanced the theory of selective reversibility of the silver salts in the sensitive film for certain wave-lengths, and it was in part to determine whether the tendency of a line to reverse was a function of the wave-length that the present investigation was undertaken.

As I showed several years ago, the Clayden effect, or the type of reversal giving rise to the phenomenon of dark lightning, results from the action of a light-shock on the plate before its exposure to diffuse light. The effect of this light-shock, which must be of very brief duration, is to decrease the sensibility of the plate, resulting in a less energetic action during the subsequent illumination. I made no attempt at the time to determine the maximum duration of the light-shock which would still give the Clayden reversal, but expressed the opinion that it could not exceed 1-10000 of a second. This opinion was based on a single experiment, and I have since found that by a suitable adjustment of the conditions the duration may be as great as 1-1000 of a second, though only a very slight trace of reversal occurs under these conditions.

It appears to me now that there are at least four different types of photographic reversal, or perhaps five, if we allow the chemical treatment of the plate between two exposures. As any one of these four types is liable to occur in any photographic work, when the proper conditions are fulfilled, it may be well to enumerate them at the beginning.

First type.—The ordinary overexposure reversal, which occurs

when the plate is given three or four hundred times its normal exposure and then developed in the usual way.

Second type.—The reversals produced by developing the plate in full lamplight, the plate having been more or less overexposed to begin with. This type has been extensively studied by Nipher, the results of his experiments being given in the *Proceedings of the St. Louis Academy of Science.*

Third type.—This type must occur frequently, though I never remember to have seen it described. It happens when a normally or underexposed plate is developed and then exposed to light for a minute or two before the hypo bath. The fogging, which is usually of a reddish-brown color, does not occur on the portions of the plate where there is a developed image, and even if this image is very feeble it remains clean and almost transparent. I first noticed this effect in some photographs of spectra which showed strong reversals along the edges where the illumination must have been very feeble, and was unable to explain it. Further experimenting showed that it had resulted from turning up the light before the plate had been thoroughly fixed. Doubtless this effect has been described time and again in the photographic journals, but it was new to me, and may be to some others. Reversals of this type appear in the second figure of Plate XII illustrating my paper on "Screens Transparent Only to Ultra-Violet Light" (ASTROPHYSICAL JOURNAL, **17**, 136, March 1903).

Fourth type.—The Clayden effect, which is the type chiefly to be dealt with in the present paper. This occurs when an exposure of about 1-1000 of a second or less is given, and the plate subsequently fogged by exposure to diffuse light before development. If images of electric sparks are thrown on a plate and the plate then exposed to the light of a candle for a few seconds, the spark images will develop reversed, which is not the case if the exposure to candle light precedes the impression of the spark images.

Fifth type.—I have found that the condition produced in the sensitive film by light-shock can be imitated by treating the plate, after exposing portions of it to the action of a feeble light for a few seconds, with an oxidizing bath of bichromate of potash

and nitric acid. If the plate is dried, and then fogged by candle light and developed, the previously exposed portions will come out reversed.

This effect is shown in Plate XXII, Fig. 4. A series of spark images was impressed on the plate, which was then covered with a piece of black paper in which a narrow slit had been cut. A number of images of this slit were then impressed on the plate by exposure to the light of a candle. If the plate in this condition were then fogged by candle light and developed, the spark images would come out reversed and the slit images not reversed. Before fogging it, one end (the upper in the print) was immersed for a few minutes in a very dilute solution of bichromate of potash, slightly acidified with nitric acid. It was then dried, exposed to candle light, and developed. In the lower portion of the print we find the sparks black and the slit images white; in the upper portion both sets of images come out dark, the reversal of the sparks being much stronger than on the untreated portion of the plate.

In the present paper I propose to discuss the Clayden effect, not only in connection with the selective reversibility hypothesis adopted by Professor Trowbridge to explain his spectrum photographs, but also in relation to the time factor, and radiations other than light, such as the Becquerel and Roentgen rays, which are quite different in their action from light.

I shall, in dealing with the subject, speak of the initial exposure of brief duration as the light-shock. The subsequent illumination which causes the reversal of the impression of the shock I shall call the fogging exposure.

The first subject investigated was the relation of the phenomenon to the wave-length of the light. The light-shock in this case was administered by exposing the plate to the spectrum of one or more sparks between cadmium electrodes by means of a small quartz spectrograph. Even with a small diaphragm the illumination by a single spark yielded a developable image of the spectrum down to the extreme ultra-violet. Six spectra were impressed on the same plate with different sized diaphragms: the plate was then exposed to the light of a candle

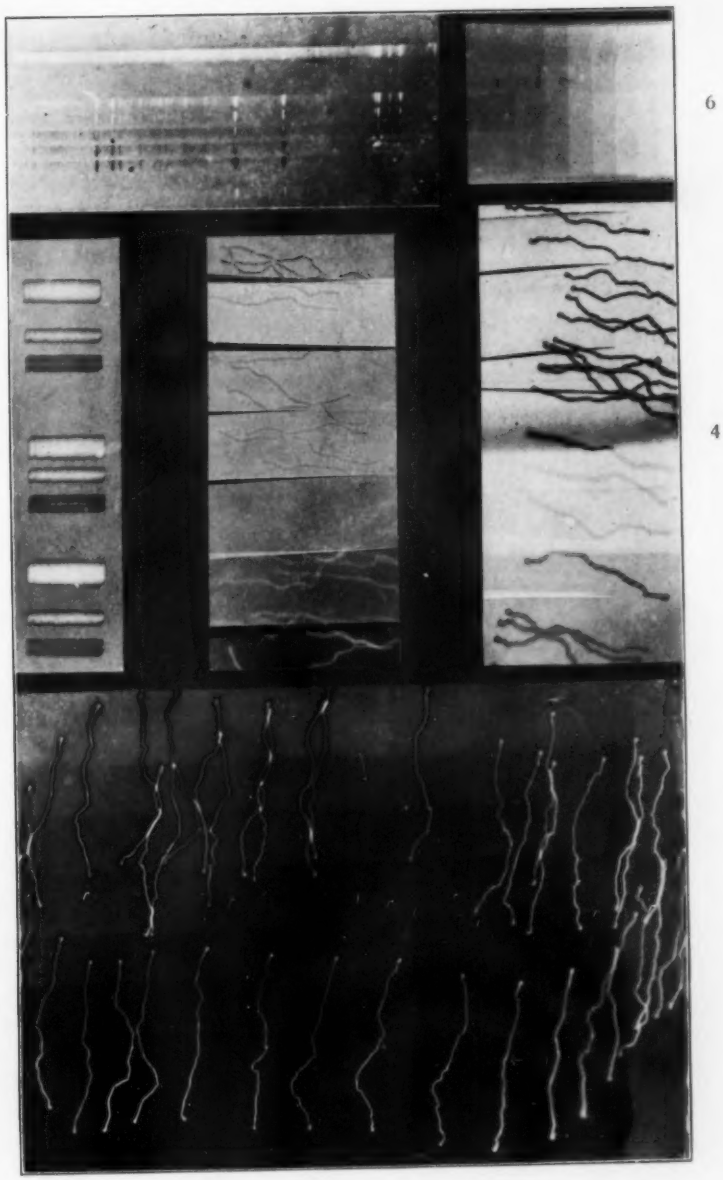
for a few seconds and developed, the result being reproduced in Plate XXII, Fig. 1. It will be seen that the lines and the continuous background come out positive in the two upper spectra, showing that if the shock is too intense, no reversal takes place —a circumstance in which the Clayden effect differs essentially from ordinary reversal due to overexposure. Professor Trowbridge says that his reversals occur where bright lines fall on a continuous background, and considers the reversing action proportional to the product of the two effects. If his reversals are of this nature (Clayden effect), this cannot be the case, for by making one factor (the light-shock) large, no trace of reversal appears. As I shall show presently, this statement requires some modification, for as we increase the intensity of the shock, we can by increasing the fogging exposure still get reversal. As I said in my previous note, it appears to me probable that in the case of photographs of spectra of single sparks in narrow capillaries the shock was the almost instantaneous exposure to a bright-line spectrum of exceeding brief duration, followed by an exposure to a superimposed continuous spectrum of longer duration, which may have been due to incandescence of the inner wall of the capillary tube, or to phosphorescence of the gas. By employing a tube with a bore of about 0.25 mm I have obtained reversed lines in the blue with single discharges of a medium-sized induction coil and condenser.

The fact that the faint continuous spectrum of the spark is uniformly reversed shows that there is no selective reversibility so far as the initial light-shock is concerned.

I next endeavored to determine whether the wave-length of the fogging light had anything to do with the matter, in which case we should expect reversals in some parts of the spectrum and not in others, in the particular case where the fogging illumination was spread out into a spectrum, as in Professor Trowbridge's photographs.

Having already found that fogging the plate with X rays never gave reversals of spark images, it occurred to me that possibly ultra-violet light might act in a similar manner. Having impressed a number of spark images on the plate, it was illumi-

PLATE XXII.



PHOTOGRAPHIC REVERSALS.

nated with light of wave-length in the neighborhood of $\lambda = 2300$, from a discharge between cadmium electrodes, a screen provided with a slit being placed in the focal plane of the quartz spectrograph, with the plate a short distance behind it. The spark images were not reversed, and it appeared at first sight as if ultra-violet light of this wave-length acted like the X rays. I was, however, not willing to accept this conclusion without further study, since the fogging illumination in this case consists in reality of a number of feeble light-shocks; that is, it is of much briefer duration than in the case of candle light. In the first experiment the fogging illumination by ultra-violet light was produced by the passage of perhaps a score of sparks before the slit of the spectrograph. To get a feebler illumination of longer duration I moved the next plate to a distance of about two meters from the screen and let the coil run for about a minute. The room was absolutely dark, the spark terminals and the front of the spectrograph being covered with heavy black cloth, so that the only light that reached the plate was of the wave-length above mentioned. On this plate the spark images which had been previously impressed were strongly reversed, showing that the time factor comes into play in the case of the fogging light as well as in that of the light-shock, and that ultra-violet light is as efficient as any other, if it is not of too brief duration. This appears to dispose of the idea of selective reversibility, at least so far as the Clayden effect is concerned.

Investigation of the time factor.—To determine the maximum duration of time which the light-shock may have and still reverse, the following method was used. A disk of cardboard 50 cm in diameter was mounted on the shaft of an electric motor, the speed of which could be determined by the tracing of a tuning-fork on a smoked metal plate mounted on the same shaft. Near the rim of the disk a number of narrow slits were cut, varying in width from 1 mm to 5 mm. An arc light was focused on the rim by means of a large condensing lens, the image of the crater being about half a millimeter in diameter. By driving the disk at a high rate of speed intermittent flashes of very brief duration were obtained as the slits passed across the arc's image. A short

distance behind the disk a rectangular metal tube, provided with a slit 1.5 mm wide, was mounted immediately opposite the point where the image of the arc fell on the disk. Down this tube the plate was dropped, receiving in its passage before the slit light flashes of varying duration. The plate was subsequently exposed to candle light and developed. The images of the slit in the case of the briefest flashes were perfectly sharp; in other cases they were broadened, owing to the rapid motion of the plate. This made the interpretation of some of the records difficult, and it was found better, when working with flashes longer than 1-2000 of a second in duration, to lower the plate down the tube with a thread. A print from one of these plates is shown in Fig. 2. In this case there were two 1 mm slits on the rim of the disk not very far apart, then further around a somewhat wider slit, and after this a still wider one. It will be seen that the slit images formed by the two very short flashes are completely reversed, while the others are reversed on their edges only.

If the plate moves during the exposure, as was the case in this photograph, it is obvious that the edges of the slit image will receive less exposure than the center, which accounts for the partial reversal. As the result of exposing about two dozen plates, it was found that the duration of the shock could be as long as 1-1000 of a second, and still yield reversals. It was only by carefully regulating the intensity of the fogging light and the duration of the development that these reversals could be obtained. When the duration is less than 1-2000 sec. reversals could be obtained without difficulty. Flashes varying in duration from 1-15000 sec. to 1-500 sec. were studied, and it was found that as the duration of the shock was increased the reversals became weaker, the images finally failing to appear at all on the plate, notwithstanding the longer duration of the flash. On still further increasing the duration the images came out not reversed. There may be some connection between the condition in which the light-shocks fail to develop at all, and the zero condition of the plate described by Nipher.

The experiment in which the fogging of the plate was effected

by exposure to ultra-violet light furnished by a quartz spectrograph shows that the time factor plays a rôle in the case of the fogging light as well as in the light-shock.

It was found that if the fogging light was rather intense, but of short duration, the image of the light-shock did not reverse; if the light was less intense, but of a little longer duration, no trace of the shock appeared; while if the light was still less intense, and of somewhat longer duration, the image came out reversed. With a suitable ratio of intensities and durations of time, it is possible to superpose two impressions on a photographic plate, only one of which appears on development.

This effect is shown in Fig. 3. A series of spark images of equal intensity was impressed on the plate, which was then fogged in sections, the lower strip being exposed to the light of one spark at a distance of a meter, the next to the light of four sparks at a distance of two meters, the next to nine sparks at three meters, and so on. The total amount of fogging light was thus approximately the same in each case, though it was found that considerably greater action was produced by a large number of sparks at a considerable distance than by a single spark close to the plate. It will be noticed that on the third strip from the bottom there is scarcely a trace of the spark images. The ratio of the times of duration of the shock and the fogging light was in this case about 1 : 9. On the two strips below this one the sparks appear not reversed, while on all the strips above reversal has taken place.

A more careful quantitative investigation of these effects is much to be desired, with apparatus of such design that the duration and intensity of both the light-shock and fogging light can be accurately controlled.

I am of the opinion that the result of such an investigation would be the establishment of the fact that with very brief and intense light-shocks, comparatively intense fogging light of short duration will yield reversals, while in the case of shocks of say 1-1000 second duration, the fogging light must be feeble and of long duration in order that reversals may be obtained. My plates appear to indicate this qualitatively, but quantitative

data could doubtless be obtained with suitable apparatus. As I shall show later, it is possible to administer the shock in such a manner that it comes out reversed even when the fogging light is the flash of a single spark.

I have tried to obtain some idea of the action of the light-shock, by attempting to transform its effect on the plate into an effect similar to that produced by ordinary exposure, by means of the action of various chemical agents. These experiments were all failures, but the interesting fact was ascertained that an ordinary exposure appeared to be transformed into a shock exposure by the action of a dilute bath of bichromate of potash slightly acid with HNO_3. This effect is shown in Fig. 4. A series of spark images was impressed on the plate, and then a series of images obtained by illuminating the plate with the light of a candle shining through a slit in a piece of black paper. One-half of the plate was then dipped into the bath, washed and dried, exposed to the light of a candle, and developed. A print from this plate is reproduced in Fig. 4. On the upper portion, which was treated with bichromate, both the spark images and slit images appear reversed; on the lower the latter are not reversed. This experiment merely shows that a plate which has been exposed to light in certain places and then treated with the bichromate solution is less sensitive to the action of subsequent illumination on the spots which have previously received light. The condition may appear at first sight to be similar to that produced by a light-shock, but there is in reality no connection between the two, for while light-shocks not followed by fogging can be developed as not reversed images, the "bichromatized images" do not develop at all, unless the plate is fogged before development.

The nearest approach which I have been able to make to the transformation of the effect of a light-shock into that due to ordinary exposure, is by the action of the X rays. It was found that spark images could not be reversed under any circumstances, if the plate was fogged by these rays instead of candle light. To prove that the case was not analogous to the one in which ultra-violet light failed to give reversals owing to the

comparatively brief duration of the illumination, long exposures were made with the X-ray tube at a considerable distance. Not only were reversals never obtained, but it was found that, after a brief exposure to the rays, fogging the plate by lamplight failed to reverse the spark images. This seemed very remarkable, for it was subsequently ascertained that X-ray images could be reversed even when produced by long exposure to feeble radiation, by subsequent exposure of the plate to lamplight. This effect is shown in Plate XXII, Fig. 5.

The spark images were impressed first. The plate was then exposed in vertical strips to the action of the X rays for varying lengths of time, the left-hand strip receiving the longest exposure, while the right-hand strip was not exposed at all. Following this, came an exposure in horizontal strips to lamplight, the lower strip having the longest exposure, and the upper none at all. It will be seen that there is no trace of reversal in the upper left-hand corner, where the fogging is due almost wholly to X rays, while reversed edges appear on all of the sparks in the lower right-hand corner, where the fogging was due to light; moreover, in the lower left-hand corner, where the X-ray fog preceded the light fog, the images are not reversed.

On investigating the matter further I found that shocks administered by single powerful flashes of X rays were reversed by subsequent exposure to lamplight. In this case, however, the time element appears to be without much influence, for images formed by long exposure to very feeble X radiation reverse in the same manner. This seems very remarkable, when we consider the fact that exposure to these rays changes the condition produced by light-shock in some manner, so that it is impossible to reverse it by further fogging.

The reversal by X rays is illustrated in Fig. 6. A plate was wrapped up in black paper and exposed to the radiation for several minutes, a vertical iron rod shielding the center strip of the plate. The plate was then exposed to lamplight for different lengths of time in strips perpendicular to the shadow of the iron rod. On development it was found that on the end of the plate which had received the shorter exposures to light, the central

strip came out lighter than the background, while on the opposite end of the plate it was darker. At a certain point near the center of the plate all trace of the shadow of the rod had disappeared, showing that exposure to X rays for some time and then to light for a certain time produces an image no blacker than the light alone would have produced.

I next ascertained that if the plate be exposed simultaneously to light and X rays, the latter inhibit the action of the former. A candle and an X-ray tube were set up at some little distance apart in front of a plate, the latter being much nearer the plate, however, owing to its less energetic action. An iron rod mounted in front of the plate cast two shadows upon the sensitive film, one projected by light, the other by X rays. After exposure the plate was developed, with the curious result that one shadow was darker than the background, the other lighter, showing that the light was more energetic in its action on the area screened from the X radiation. It may be worthy of mention that both this result and the preceding one were predicted before the actual experiments were tried. The prediction was the result of an attempt to apply Bose's strain theory of photographic action[1] to the phenomena in question. This theory seemed rather promising at first, especially as it enabled me to predict new phenomena, but it failed to account for so many things that I was finally forced to abandon it.

The action of other stimuli was next investigated. It has long been known that pressure marks on the film can be developed. I found that if the plate was fogged by lamplight before developing, the pressure marks came out reversed. It then occurred to me to try the effect of light-shocks on pressure marks, and I found to my surprise that the flash of a single spark was as effective in reversing the pressure mark as the exposure to the lamp. The pressure marks can also be reversed by exposure to X rays.

As a result of numerous other experiments, I finally found that if we arrange the stimuli in the following order, pressure marks, X rays, light-shock, and lamplight, an impression of any

[1] J. C. Bose, *Proc. Roy. Soc.*, **70**, 185, 1902.

one of them can be reversed by subsequent exposure to any other following it in the list, but under no circumstances by any one preceding it. For example, pressure marks can be reversed by any one of the other three stimuli, while X-ray images are reversed only by light-shock and lamplight.

Experiments with Becquerel rays have given rather uncertain results. Pressure marks can be reversed by them, and they in turn can be reversed by lamplight, but these were the only two cases in which reversals were obtained, which makes it difficult to fit the rays into the series and still have the rule hold.

These experiments show that the effects of the different kinds of stimuli on the sensitive film are quite different. Much more experimental work will have to be done before any definite notion can be obtained as to the nature of the changes produced by the action of radiation of any sort, and it is hoped that the experiments described in this paper may prove suggestive to others. Doubtless an exhaustive study of the action of various chemical agents on the plate between the two exposures would throw much light on the cause of the reversals.

If I interpret the strain theory correctly, the application to these phenomena would be to assume that the light-shock produces a negative strain, while lamplight produces a positive strain, either of which yields an image on development. The reversal in cases where the lamplight follows the impression of the light-shock could be explained by assuming that the negative strain has to be undone before the positive strain can begin; consequently these parts of the plate lag behind the parts which have not received the light-shock. We should then have to assume that the positive strain once started can be continued by a stimulus which, acting first, would have produced a negative strain, in order to account for the fact that exposures to lamplight are not reversed by light-shocks. Moreover, it is difficult to explain on the strain theory that two different stimuli acting in succession may produce only the same effect as one of them acting alone. It appears to me that the strain theory would lead us to suppose that the negative strain produced by the first stimulus might be exactly neutralized by a stimulus which pro-

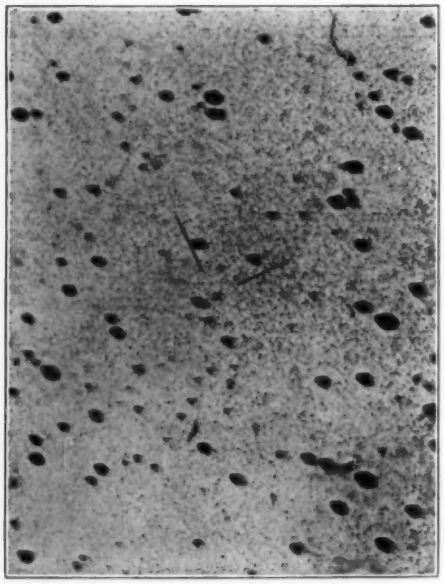
duces a positive strain, the plate returning to its original condition, *i. e.*, not darkening on development. This is never the case.

In cases where reversed lines appear in the spectrum which are suspected of being photographic in origin, *i. e.*, not true absorption lines, the following precautions should be taken. Repeat the exposure a number of times, using successively smaller diaphragms in front of the prism. If the reversal is ordinary solarization due to overexposure, it should disappear when the intensity of the light is sufficiently reduced. It seems to me that in such cases the reversed line should be bordered by bright edges, which does not seem to be the case in the photographs published by Professor Trowbridge. If the Clayden effect is suspected, the source of light should be examined with a revolving mirror, to determine whether a dual illumination is present. The speed of the mirror should not be too great, otherwise the phosphorescence (if it exists) which follows the very brief bright line flash, may be spread out to such an extent that no trace of it appears. This may account for the failure to obtain evidence of a dual illumination in the case of the heavy discharges in quartz tubes.

JOHNS HOPKINS UNIVERSITY,
Baltimore, Md.,
May 1903.

PLATE XXIII.

N.



S.

Scale 1 mm = 13″.

REGION OF *NOVA GEMINORUM*
February 21, 1903.

NOVA GEMINORUM.

AN EARLY PHOTOGRAPH AND PHOTOMETRIC MAGNITUDES.

By J. A. PARKHURST.

THE negative of the *Nova* region taken 1903, February 21, $8^h\ 22^m$ to $8^h\ 42^m$, C. S. T., was mentioned in *Bulletin* No. 19 of the Yerkes Observatory,[1] but the cut made to illustrate it was not successful and was therefore omitted. An untouched copy is reproduced here, Plate XXIII, showing a star of magnitude 14.5 apparently coincident with the present position of the *Nova*. The photometric magnitudes of four faint stars near the *Nova* are as follows :

Star No.	Mag.	Measures
5.....	13.11	3 nights
6.....	12.99	2 "
3.....	14.89	1 "
1.....	13.34	1 "

The numbers given for identification are those on Professor Barnard's drawing of the region on page 304 of the *Bulletin* No. 19. It will be seen that the *Nova* is a little brighter than star No. 3; its magnitude on February 21 is therefore estimated at 14.5. It will be noticed that the photograph agrees with Professor Barnard's micrometer measures in placing the *Nova* farther north than star No. 1, whereas the object taken for the *Nova* on the photograph by Mr. Dugan at Heidelberg February 16, and reproduced in *Popular Astronomy* for May 1903, page 260, is a little farther south than star No. 1, possibly due to the retouching of Mr. Dugan's print.

Following are the photometric magnitudes of the *Nova*, preceded by a list of standard stars and the comparison stars so far used. The standards, *l*, *g*, and *h*, were measured both at Har-

[1] ASTROPHYSICAL JOURNAL, 17, 300, May 1903.

vard (*H. C. O. Annals*, Vol. XLV) and at Potsdam, the difference between the means, 0.20 magnitude, agreeing closely with the systematic difference between the two catalogues; these stars seem therefore well adapted for standards. For the comparison stars, *b*, *c*, *d*, and *e*, the magnitudes given in the columns headed H. and P. are the means of three nights' comparison with the standards given above, H. being on the Harvard basis, and P. the Potsdam.

STANDARDS.

Harvard and Potsdam.

Star	*B. D.*		*H. C. O.*	*P. D. M.*
	No.	Mag.		
l.....	+29°1307	7.2	7.36	7.22
g.....	30 1318	7.0	7.13	7.50
h.....	31 1363	7.0	7.23	7.60
	Mean		7.24	7.44

COMPARISON STARS.

Star	*B. D.*		H.	P.
	No.	Mag.		
b.....	29°1342	8.2	7.79	7.99
c.....	29 1320	7.8	7.46	7.66
d.....	30 1306	8.6	9.09	9.29
e.....	30 1302	9.2	9.32	9.52

MEASURED MAGNITUDES OF THE *NOVA*, BASED ON THE HARVARD SCALE.

	G. M. T.	Mag.	Seeing		G. M. T.	Mag.	Seeing
1903, March	27.715	8.51	fair	1903, April	7.574	9.19	clouds, moon
	28.636	8.71			8.593	9.19	moon
	29.603	8.85			16.661	9.31	good
	30.673	8.76	fair		26.671	9.63	fine
	31.588	8.89	good		27.632	9.41	good
April	3.564	8.91	clouds		30.591	9.74	good
	4.583	8.96	moon	May	3.621	9.56	moon
	6.574	9.19	moon		6.634	9.50	
					7.593	9.84	moon, good

The resulting magnitudes of the *Nova* should be compared with Professor Barnard's (given elsewhere in this number), which are based on photometric measures of comparison stars, on the Harvard system.

Fluctuations, similar to those of *Nova Persei*, are clearly shown, as indicated in the measures given in *Bulletin* No. 19, and noted in Harvard *Circulars* Nos. 127 and 128.

YERKES OBSERVATORY,
May 9, 1903.

OBSERVATIONS OF *NOVA GEMINORUM.*

By E. E. Barnard.

My estimates of the magnitudes of the *Nova* were made by comparison of its light with neighboring stars, the magnitudes of which have been determined by Mr. Parkhurst with the photometer.

The instruments used were the finders of the forty-inch and twelve-inch refractors, and on the last few dates (May 7, 8, 9, and 10) the twelve-inch, as the star could not be seen in the finder because of moonlight and haze.

The observations of April 27 were made through a very hazy sky, and the estimations were more or less difficult.

At first the *Nova* was of a strong red color, but it has since become colorless. On March 29 there was not much color seen in the twelve-inch, though it was a little redder than *B. D.* $+29^{\circ}$ 1342. On April 3, with the same instrument, it was noted as "a little reddish;" April 22, also with the twelve-inch, it was colorless and there seemed to be a slight difference of focus. On April 27 and 28 no trace of color was seen with the forty-inch.

In the first observations the *Nova* showed no difference in focus from that of an ordinary star (see Astrophysical Journal, **17**, 302, 1903). In the later observations there seems to be a sensible change in the focus; this, however, has not been properly verified.

On April 27 careful observations for focus were made with the forty-inch, with the following results:

Focus for *Nova*, scale reading	-	2.36 in. (5 obs.).
Focus for star, scale reading	-	2.28 in. (5 obs.).
Difference, *Nova* − star	-	= + 0.08 in. (= 2.0 mm).

The seeing was poor and the settings discordant for both objects. I think, however, that this indicates a real change of focus, for when either object was in the best focus the other was somewhat ill-defined. Cloudy weather has since prevented verification of this with the forty-inch.

On April 6 the crimson image seen on March 30 (*loc. cit.*, p. 303) was still present, though not so strong and definite. On April 27 it had entirely disappeared, the out-of-focus image of the *Nova* resembling that of an ordinary star. Cloudy weather had prevented any observation by me with the large telescope between April 7 and 27. I am therefore unable to say just when this change took place; it would perhaps not be far from the middle of April.

OBSERVED MAGNITUDES OF *NOVA GEMINORUM*.

	Central Standard Time.	Mag.
1903, March 27	$12^h\ 30^m$	8.00
29	9 0	8.81
30	9 0	8.82
31	7 20	8.84
April 3	8 0	8.96
4	7 40	9.04
6	9 0	9.15
7	10 20	9.22
9	8 0	9.12
16	7 40	9.12
17	9 0	9.20
22	7 50	9.20
24	8 15	9.92
26	8 30	9.81
27	8 30	9.96
28	8 30	10.18
May 3	8 20	9.80
6	8 10	9.80
7	9 10	9.87
8	8 30	9.77
10	8 10	9.77
18	8 30	10.02
19	8 30	10.07

At the observation of March 27 the star was very low and the estimated magnitude is unreliable.

YERKES OBSERVATORY,
May 11, 1903.

Minor Contributions and Notes.

PARALLAX OF THE BINARY SYSTEM δ *EQUULEI*.[1]

The object of this communication is to present a value of the parallax of δ *Equulei* obtained by using as data the elements of the orbit derived from micrometrical measures and the relative velocity of the components in the line of sight furnished by spectroscopic observations. While the result given is merely provisional, one to be improved when better elements of the orbit are available, as they no doubt will be after two or three years more, yet it is thought that it has already a measure of certainty which places it in the list with the more accurately determined stellar parallaxes. Moreover, the manner of its derivation differs from previous determinations. The use of comparison stars and the uncertainties of their assumed distances are eliminated. In theory the method leads to an absolute value of the parallax, and not to a relative one, as is necessarily the case when comparison stars are employed.

The mathematical relations connecting the elements of the orbit of a binary, the relative velocity of its components in the line of sight, and the parallax of the system, have long been known. Applications have hitherto been wanting, for the reason that no double stars had been found which furnished all the data needed. δ *Equulei* has proven an exception. The elements of its orbit are approximately known, and in 1901, at the time of the last periastron passage, the relative velocity of the components in the line of sight was so great that the spectra of the two stars were displaced to a measurable extent.

In the *Monthly Notices* of the Royal Astronomical Society for March 1890, Professor Arthur A. Rambaut has given the following simple formula for computing the parallax of a binary from the data here considered:

$$\pi = \frac{la^2\sqrt{1-e^2}\sin(\phi-\lambda)\sin i}{VPr\sqrt{1-e^2\cos^2\phi}}.$$

In this equation P denotes the periodic time, a the mean distance, e the eccentricity, i the inclination, r the radius vector, λ the angle

[1] *Lick Observatory Bulletin* No. 32.

between the line of nodes and the major axis of the true ellipse, ϕ the angle between the tangent to the orbit and the major axis, V the relative velocity of the components in the line of sight as furnished by the spectroscopic observations, l the velocity of the Earth in its orbit, and π the parallax of the system.

The elements of the orbit of δ *Equulei* are still imperfectly known. A nearly continuous record of the motion of the companion during the next three years is necessary to remove effectively the uncertainties which still exist in their values. Eight times since the discovery of this binary the companion has passed over the arc which it will describe during the next three years, and numerous observations relate to this portion of the orbit. But the measures are more or less discordant, and on this account additional ones are required to fix with certainty the direction and magnitude of the greatest apparent distance. When these measures are obtained and the elements of the orbit revised, we shall have the data which will give an accurate value of the parallax of the system. A consideration of the material at present available appears to show that the changes which will probably take place in the elements due to the revision of the orbit will not greatly alter the value of the parallax which may now be derived, and it is on this account that a provisional value is here presented.

During the past three years this binary has been followed closely at the Lick Observatory and much has been done to advance our knowledge of its orbit. It has been shown that the periodic time is about 5.7 years; that the last epoch of periastron passage was about 1901.5; that the apparent distance at periastron is about $0''.15$; that the inclination is greater than given by the trial elements which I printed in the *Publications of the Astronomical Society of the Pacific* for December 1900, and afterwards in Vol. V of the *Publications of the Lick Observatory*, being perhaps as much as 82° or 83°; and that the mean distance is probably a little larger than given by those elements. Further, it is known that the line of nodes and the projection of the major axis of the orbit are nearly coincident.

If we retain the line of nodes and the angle between the line of nodes and the major axis, the true ellipse as given by my published elements, and put the mean distance equal to $0''.28$ and the eccentricity equal to 0.46, we get $0''.151$ and $0''.409$ as the periastron and apastron distances.

The relative velocity of the components in the line of sight at the epoch of periastron passage, as determined by the observers using the

Mills Spectrograph,[1] was about 20.3 miles per second. At the same time the Earth's orbital velocity was about 18.2 miles per second. At periastron ϕ becomes 90° or 270°, and with $\lambda = 179°$, we have $\phi - \lambda = 91°$. Substituting these values in Professor Rambaut's formula we get

$$\pi = 0''.071.$$

It is evidently impossible to give the probable error of this result. Some of the quantities upon which it depends are much better determined than others. It happens that those which appear to be the most uncertain may vary considerably without greatly affecting the resulting value of the parallax. For example, considerable variations may take place in the values of i and λ without greatly changing the values of sin i and sin $(\phi - \lambda)$ which appear in the formula. Of the other quantities those which appear the least certain are the mean distance and the eccentricity. From a consideration of all the past measures it appears highly improbable that the apastron distance can be as much as $0''.05$ greater or less than the value used above. If we vary the apastron distance and eccentricity together so as to keep the already well-determined periastron distance constant, and further retain the other elements of the computation as used above, we shall find that the apastron distance and parallax increase together, but the former at about four times the rate of the latter. From this consideration it appears improbable that the parallax will be altered so much as $0''.012$ owing to changes which take place in the values of a and e due to the revision of the elements of the orbit.

The mass of the system corresponding to the parallax given above, and the mean distance and the periodic time used in its derivation, is 1.89, the mass of the Sun being taken as unity. The components of this pair are slightly unequal in brightness, and perhaps also in mass. One may be as massive as the Sun, but it cannot much exceed it.

The mean distance at which these stars perform their revolutions is about four times that of the Earth from the Sun. But owing to the eccentricity of the orbit the range in distance is enormous. At periastron the stars are separated by a space only a little greater than two astronomical units, while at apastron it is five of these units.

It would form an interesting analytical problem to investigate the effect of tidal action upon the relative orbit of this system. The data are pretty well ascertained. Broadly speaking the stars have spectra

[1] *Bulletin of the Lick Observatory* No. 4, and *Publications of the Lick Observatory*, 5 211.

of the solar type, and being comparable with the Sun in mass, it would seem not unreasonable to assume that their densities are approximately the same as that of the Sun.

WILLIAM J. HUSSEY.

FEBRUARY 23, 1903.

TWO STARS WITH VARIABLE RADIAL VELOCITIES.

IN the course of our most recent work with the Bruce Spectrograph on stars having spectra of the *Orion* type the two stars u *Herculis* and 57 *Cygni* have been found to show large variations in their radial velocities.

The data for these stars are as follows:

u *HERCULIS* ($\alpha = 17^h\ 14^m$; $\delta = +33^\circ\ 12'$; Mag. = 4.9).

Plate	Date	Taken by	Velocity	No. of Lines	Measured by
C23	1903, February 19	A.	− 65	5	A.
C34	March 18	F.	− 44	3	A.
DB6	May 7	A.	+101	4	A.
DB17	May 9	A.	+ 98	3	A.

This star is of especial interest on account of being a photometric variable of irregular period. The lines of its spectrum are broad and diffuse, and the measures are consequently uncertain to the extent of several kilometers.

57 *CYGNI* ($\alpha = 20^h\ 50^m$; $\delta = +44^\circ\ 0'$; Mag. = 4.6).

Plate	Date	Taken by	Velocity	No. of Lines	Measured by
DB22	1903, May 16	F.	−114	4	F.
DB24	May 17	A.	− 23	3	F.

On plate 22 the magnesium line at $\lambda 4481.4$ appears to have a second component, which is displaced toward the red by an amount corresponding to a velocity of about + 56 km. No second component can be seen on plate 24. In this connection it may be stated that on different plates we often find marked differences in the distinctness of the lines in spectra of stars varying rapidly in velocity, doubtless in part due to the change of velocity during the exposure.

In the list of plates given above those belonging to series C were taken with the short-focus camera, to which reference has already been made in our communication in the April number of this JOURNAL.

The plates of series DB were taken with a dispersion of one prism and the regular camera of twenty-four inches focal length. For this apparatus two of the prisms of the Bruce spectrograph are removed, and auxiliary castings added to support the camera tube at the necessary angle in reference to the first prism. Especial attention was given to the stability of the support, and the results obtained are entirely satisfactory in this respect. The scale of the plates is, of course, very closely one-third that given by the three prisms. In the case, however, of stars which have wide and diffuse lines in their spectra, the narrowing of these lines, and the consequent increase in the accuracy of the measures upon them, largely counteracts the effect of the smaller scale, so that the final values often compare favorably with those obtained with the use of the higher dispersion. The considerable increase in the number of measurable lines, through the additional extent of spectrum which is brought into focus, also contributes materially to this result.

EDWIN B. FROST AND WALTER S. ADAMS.

YERKES OBSERVATORY,
May 19, 1903.

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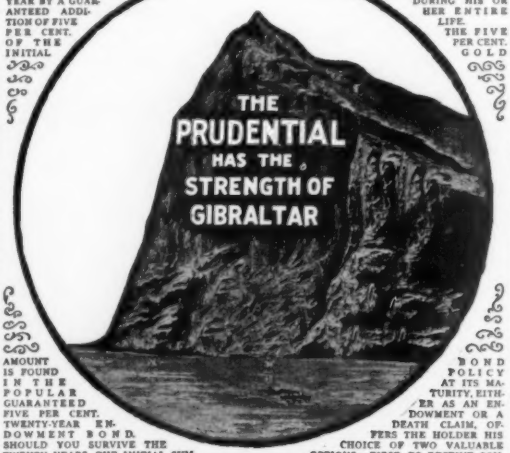

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WHEN TAKING OUT THE POLICY. AT THE END OF THE SELECTED PERIOD YOU MAY RECEIVE THESE ACCUMULATED DIVIDENDS IN CASH, OR YOU MAY APPLY THEM TO REDUCE FUTURE PREMIUMS. THE WHOLE LIFE POLICY IS ISSUED ALSO WITH DIVIDENDS PAYABLE ANNUALLY OR AT INTERVALS OF FIVE YEARS. AFTER THE POLICY HAS BEEN IN FORCE THREE YEARS, YOU MAY BORROW MONEY FROM THE COMPANY ON THE SECURITY OF YOUR POLICY. THE AMOUNT THAT MAY BE BORROWED INCREASES WITH THE NUMBER OF PREMIUMS PAID. THE COST IS LOW, AND RATES WILL BE FURNISHED UPON REQUEST. SHOULD YOU DESIRE A POLICY WHERE EITHER YOU OR YOUR BENEFICIARY WILL DERIVE THE BENEFIT, WE WOULD RECOMMEND THE ENDOWMENT POLICY. UNDER THIS PLAN THE SUM INSURED IS PAYABLE TO YOU, IF LIVING AT THE END OF THE ENDOWMENT PERIOD, OR TO YOUR BENEFICIARY IF YOUR DEATH SHOULD OCCUR PREVIOUSLY. THE LENGTH OF THE ENDOWMENT PERIOD MAY BE TEN, FIFTEEN OR TWENTY YEARS, AS YOU MAY SELECT WHEN TAKING OUT THE POLICY. THE PREMIUMS ARE PAYABLE BY YOU EITHER ANNUALLY, SEMI-ANNUALLY OR QUARTERLY DURING THE LIFE OF THE POLICY, OR THEY MAY BE LIMITED TO A TERM OF YEARS, LESS THAN THE ENDOWMENT PERIOD, IF YOU DESIRE. FOR EXAMPLE, THE PREMIUM ON A TWENTY-YEAR ENDOWMENT POLICY MAY BE PAID BY YOU DURING THE FIRST TEN YEARS IF YOU WISH. UNDER THE ENDOWMENT PLAN THE INSURED MAY NOT ONLY SECURE PROTECTION FOR HIS FAMILY, BUT HAVE A CONVENIENT AND PROFITABLE METHOD OF INVESTING HIS SAVINGS. THIS POLICY SHARES IN THE PROFITS APPORTIONED BY THE COMPANY IN THE SAME MANNER AS THE WHOLE LIFE POLICY. AFTER TWO YEARS' PREMIUMS HAVE BEEN PAID, YOU MAY BORROW MONEY FROM THE COMPANY ON THE SECURITY OF YOUR POLICY. THE POLICY HAS MANY OTHER LIBERAL PROVISIONS. SHOULD YOU DESIRE A POLICY THAT IS PAYABLE AT YOUR DEATH, BUT WISH TO LIMIT YOUR PREMIUM PAYMENTS TO A NUMBER OF YEARS, WE ISSUE WHAT IS KNOWN AS THE LIMITED-PAYMENT LIFE POLICY. THIS IS THE SAME AS THE WHOLE LIFE POLICY, EXCEPT THAT THE PAYMENTS ARE MADE BY YOU FOR TEN, FIFTEEN OR TWENTY YEARS ONLY, AS SELECTED WHEN TAKING OUT THE POLICY. IF YOU SURVIVE THE PREMIUM-PAYING PERIOD, THE POLICY IS CONTINUED IN FORCE ON THE BOOKS OF THE COMPANY, AND YOU MAY DRAW OUT YOUR DIVIDENDS, BUT NO FURTHER PREMIUM PAYMENTS ARE REQUIRED. THE POLICY IS SUBJECT TO ALL THE PRIVILEGES AND BENEFITS OF THE WHOLE LIFE POLICY. AFTER THREE YEARS' PREMIUMS HAVE BEEN PAID, YOU MAY BORROW MONEY FROM THE COMPANY ON THE SECURITY OF YOUR POLICY, AND THE AMOUNT YOU MAY BORROW INCREASES WITH THE NUMBER OF PREMIUMS PAID. SHOULD A POLICY FOR A SMALL AMOUNT BE DESIRED, ONE OF THE BEST FORMS IS THE INTERMEDIATE POLICY. IT IS ISSUED IN AMOUNTS OF $500, ON THE WHOLE LIFE, LIMITED-PAYMENT LIFE OR ENDOWMENT PLAN. THE INTERMEDIATE POLICY SHARES IN THE PROFITS APPORTIONED BY THE COMPANY, WHICH ARE CREDITED TO THE POLICY AFTER IT HAS BEEN IN FORCE FOR FIVE YEARS, AND EVERY YEAR THEREAFTER IT WILL, IF IN FORCE, BE CREDITED WITH AN ANNUAL DIVIDEND. THIS POLICY IS SUBJECT TO OTHER VALUABLE PRIVILEGES, WHICH WILL BE EXPLAINED UPON REQUEST. THE INDUSTRIAL POLICY IS VERY POPULAR, AND IS ISSUED IN AMOUNTS FROM $25 TO $500 TO PERSONS BETWEEN AGES ONE AND SEVENTY. THE PREMIUM PAYMENTS ARE MADE BY THE POLICY-HOLDER IN SMALL WEEKLY SUMS, SUCH AS TEN, FIFTEEN OR TWENTY CENTS A WEEK, AND UPWARDS, FOR WHICH OUR AGENT CALLS. THIS POLICY PROVIDES FOR PAYMENT OF THE CLAIM BY THE COMPANY IMMEDIATELY ON ACCEPTANCE OF SATISFACTORY PROOF OF DEATH, AS DO ALL THE POLICIES ISSUED BY THE PRUDENTIAL. AFTER IT HAS BEEN IN FORCE FIVE YEARS, THE INDUSTRIAL POLICY IS CREDITED WITH DIVIDENDS, WHICH ARE ADDED TO THE POLICY, SO THAT IT BECOMES MORE AND MORE VALUABLE AS IT GROWS OLDER. AT THE END OF FIFTEEN YEARS, A CASH DIVIDEND IS PAID BY THE COMPANY. THIS POLICY PROVIDES FULL PROTECTION TO PERSONS WHO WISH A SMALL AMOUNT OF LIFE INSURANCE AT MODERATE COST.

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THE FIVE PER CENT. GOLD BOND POLICY AT ITS MATURITY, EITHER AS AN ENDOWMENT OR A DEATH CLAIM, OFFERS THE HOLDER HIS CHOICE OF TWO VALUABLE OPTIONS: FIRST, TO RECEIVE COUPON BONDS IN SUMS OF $1,000 EACH, MATURING IN TWENTY YEARS, GUARANTEEING FIVE PER CENT. INTEREST PER ANNUM, PAYABLE SEMI-ANNUALLY IN ADVANCE IN GOLD. SECOND, IN PLACE OF THE BONDS, TO RECEIVE IN GOLD COIN THE SUM OF $1,318 FOR EACH $1,000 OF THE FACE VALUE OF THE POLICY. THE RESULT IS A SURE INVESTMENT, A GUARANTEED INCOME AT A HIGH RATE OF INTEREST, AND NO EXPENSE OR WORRY OVER THE MANAGEMENT OF THIS PART OF ONE'S ESTATE. MOREOVER, THE PRUDENTIAL SELLS THIS FORM OF INSURANCE UPON THE BASIS OF ABSOLUTE GUARANTEE—NO ESTIMATES, NOTHING PROVISIONAL, AND AT A PRICE SO LOW AS TO MAKE IT, FOR THE MAJORITY OF PEOPLE, ONE OF THE MOST ADVANTAGEOUS POLICIES IN THE LIFE INSURANCE MARKET. THESE POLICIES ARE ALSO ISSUED UPON THE PARTICIPATING PLAN. THE FOLLOWING ARE SOME OF THE LIBERAL FEATURES CONTAINED IN THE ORDINARY POLICIES NOW ISSUED BY THE PRUDENTIAL: AFTER ONE YEAR FROM THEIR DATE, IF THE PREMIUMS BE PAID AS STIPULATED, THE POLICIES BECOME INCONTESTABLE. DEATH FROM SUICIDE WILL NOT INVALIDATE THE POLICY AFTER IT HAS BEEN ONE YEAR IN FORCE. AFTER A POLICY HAS ONCE BEEN ISSUED AND PAID FOR THERE ARE NO RESTRICTIONS AS TO RESIDENCE, TRAVEL OR OCCUPATION, NOR WILL A PERMIT OR EXTRA PREMIUM BE REQUIRED IN CASE OF MILITARY SERVICE, WHETHER IN TIME OF PEACE OR WAR. THE MANNER OF PAYMENT OF PREMIUMS MAY BE CHANGED ON ANY SUBSEQUENT ANNIVERSARY DATE OF THE POLICY. A GRACE OF ONE MONTH, WITHOUT INTEREST, WILL BE ALLOWED IN THE PAYMENT OF ANY PREMIUM EXCEPT THE FIRST DURING THE PERIOD OF GRACE THE POLICY REMAINS IN FULL FORCE. THE CASH LOAN PRIVILEGE CONTAINED IN ORDINARY POLICIES VIRTUALLY MAKES EVERY POLICY A NEGOTIABLE BOND. THE INSURED MAY AT ANY TIME WHILE THE POLICY IS IN FORCE NAME A NEW BENEFICIARY. THE AMOUNT INSURED UNDER THE POLICY IS PAYABLE IN ONE SUM, BUT MAY BE MADE PAYABLE IN ANY NUMBER OF EQUAL ANNUAL INSTALMENTS, FROM TWO TO TWENTY-FIVE, OR IT MAY BE MADE PAYABLE TO THE BENEFICIARY IN CONTINUOUS INSTALMENTS—THAT IS, IT MAY BE MADE PAYABLE IN EQUAL ANNUAL INSTALMENTS TO CONTINUE AT LEAST TWENTY YEARS, AND AS LONG THEREAFTER AS THE BENEFICIARY SHALL LIVE. EACH INSTALMENT, EXCEPT THE FIRST, WILL BE INCREASED BY SUCH ANNUAL DIVIDEND AS MAY BE APPORTIONED BY THE COMPANY AT THE TIME THE POLICY BECOMES PAYABLE AS A CLAIM. THE AMOUNT INSURED, OR ANY PORTION THEREOF NOT LESS THAN $1,000, MAY BE LEFT DURING THE LIFETIME OF THE BENEFICIARY IN TRUST WITH THE COMPANY, WHICH WILL PAY THEREON, AS LONG AS THE SAID AMOUNT REMAINS IN TRUST, INTEREST AT THE RATE OF THREE PER CENT. PER ANNUM, TOGETHER WITH SUCH ANNUAL DIVIDEND AS MAY BE APPORTIONED BY THE COMPANY. THE SAID TRUST FUND SHALL BE PAID AT THE DEATH OF THE BENEFICIARY TO THE EXECUTORS, ADMINISTRATORS OR ASSIGNS OF THE BENEFICIARY, BUT MAY BE WITHDRAWN AT ANY TIME, WITH ACCRUED INTEREST. IN THE CASE OF POLICIES MATURING AS ENDOWMENTS, THE INSTALMENT PRIVILEGE OR TRUST FUND PRIVILEGE MAY BE EXERCISED BY THE INSURED FOR HIS OWN BENEFIT. THE FOLLOWING VALUABLE PRIVILEGES ARE EXTENDED TO THOSE WHO MAY DISCONTINUE THEIR PREMIUMS: IF THE POLICY LAPSE FOR NON-PAYMENT OF PREMIUM AT ANY TIME AFTER HAVING BEEN IN FORCE ONE FULL YEAR, THE COMPANY WILL GRANT EXTENDED INSURANCE. THAT IS, IN THE CASE OF A POLICY LAPSED AT THE END OF ONE YEAR, OR ANY TIME THEREAFTER, THE POLICY-HOLDER WILL STILL BE INSURED FOR A FURTHER PERIOD, GIVEN IN THE POLICY, AND IN CERTAIN CASES UNDER ENDOWMENT POLICIES, THE POLICY-HOLDER IS INSURED TILL THE END OF THE ENDOWMENT PERIOD, AND IN ADDITION RECEIVES, AT THAT TIME, A CERTAIN AMOUNT IN CASH AS A PURE ENDOWMENT. THUS THE POLICY-HOLDER IS COMPLETELY AND AUTOMATICALLY PROTECTED IN EVERY CASE. IF DESIRED, INSTEAD OF EXTENDED INSURANCE FOR THE FULL AMOUNT OF POLICY, A PAID-UP POLICY FOR A SMALLER AMOUNT MAY BE HAD. SUCH A POLICY MAY BE OBTAINED AT ANY TIME AFTER THE ORIGINAL POLICY HAS BEEN THREE YEARS IN FORCE (TWO YEARS IN CASE OF ENDOWMENTS) BY MAKING PROPER APPLICATION AND SURRENDERING THE ORIGINAL POLICY TO THE COMPANY. THEN, TOO, THE INSURED IS GIVEN AN OPPORTUNITY, PROVIDED ALL DUE PREMIUMS HAVE BEEN PAID, OF REALIZING, IF DESIRED, THE CASH VALUE OF THE POLICY ITSELF, THAT IS, OF SURRENDERING THE POLICY TO THE COMPANY IN RETURN FOR A LIBERAL CASH VALUE, THE AMOUNT OF WHICH INCREASES WITH EACH PREMIUM PAID, AND IS PLAINLY STATED, FOR EACH YEAR, IN THE POLICY. THE POLICY ALSO CONTAINS LIBERAL PROVISION FOR REINSTATEMENT IN CASE OF LAPSE. APPLICATIONS FOR LIFE INSURANCE MAY BE MADE TO ANY OF THE COMPANY'S AGENTS, AND A SPECIMEN POLICY WILL BE SENT YOU AT ANY TIME UPON REQUEST. WRITE FOR FURTHER PARTICULARS TO THE PRUDENTIAL INSURANCE COMPANY OF AMERICA, HOME OFFICE, NEWARK, N. J.

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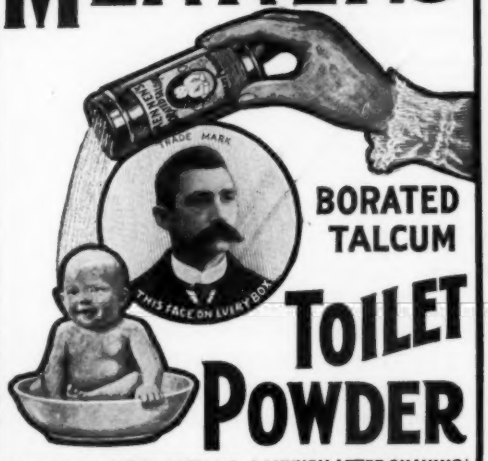

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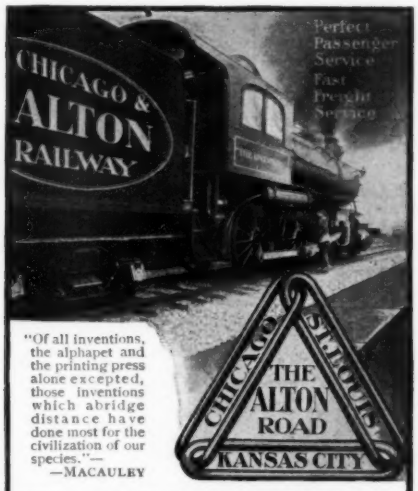

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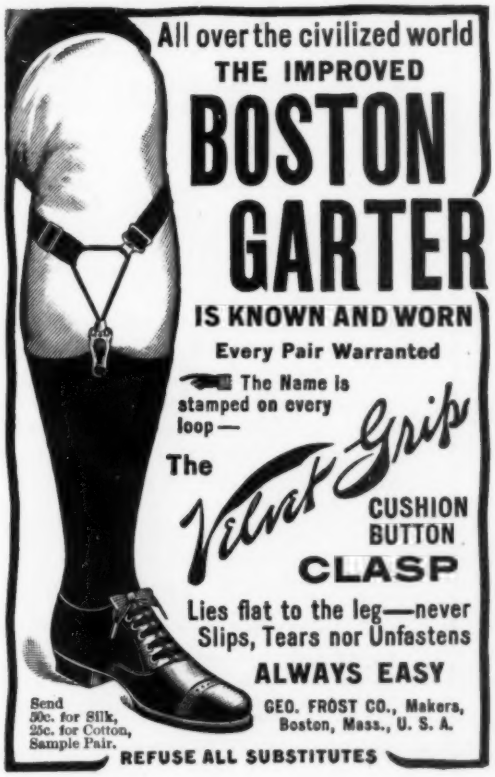

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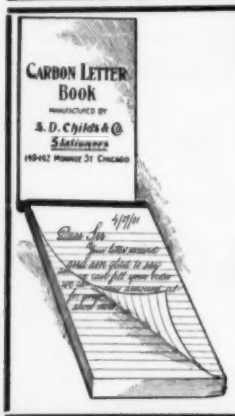

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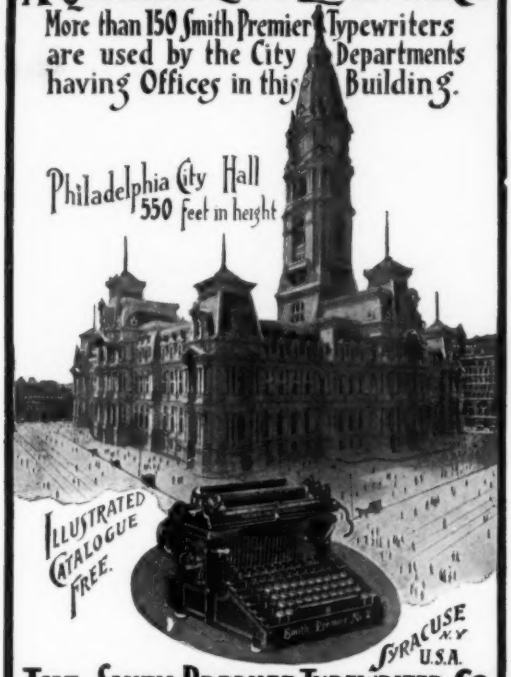

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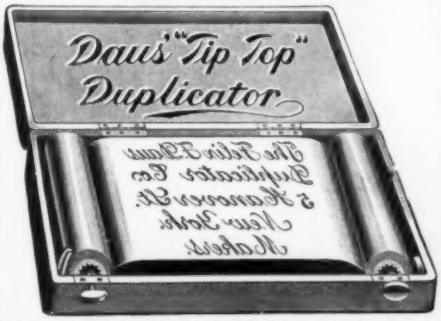

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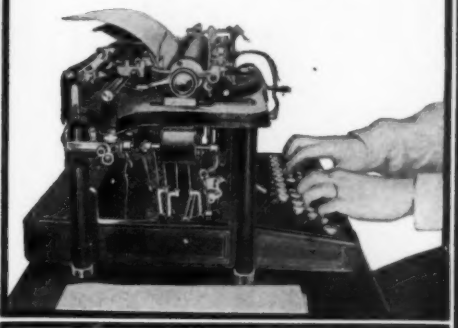

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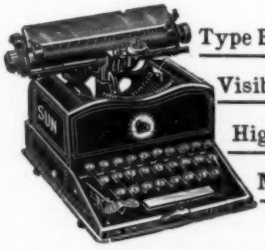

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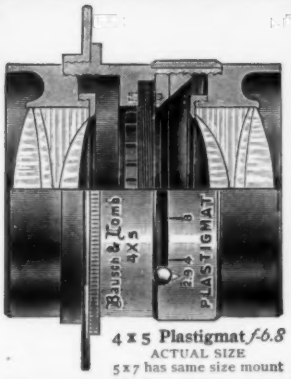

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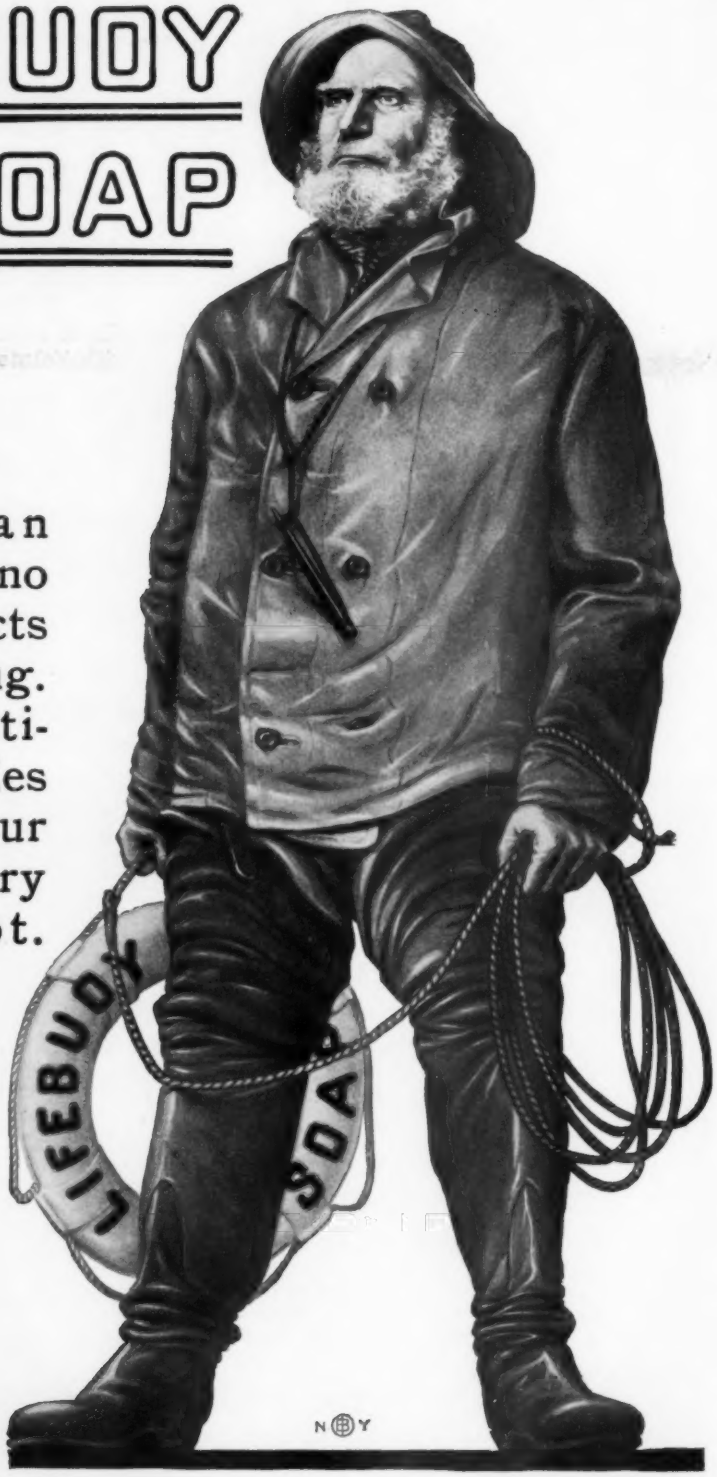

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